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# **Discrete-Event Simulation for Hospital Resource Planning – Possibilities and Requirements**

by

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## **ABSTRACT**

The delivery of health care services has been under pressure due to limited funding and increasing demand. This has highlighted the need to increase not only the effectiveness but also the efficiency of health care delivery. Discrete-event simulation has been suggested as an analysis tool in health care management to support the planning of health care resources.

The overall purpose of this thesis is to investigate the possibilities and requirements for using discrete-event simulation in analyzing and planning the use of hospital resources. This is achieved by three case studies that focus on improvements in patient flow of emergency patients that require a radiology examination, intensive care unit capacity planning and operating room allocation strategies, respectively.

The first case investigates the current stage of digitization and process orientation in hospital care as a prerequisite for efficient process simulation and analysis. The study reveals an emergency-radiology patient flow process that is not very well measured and uncovers disparate information systems storing incompatible and fragmented data. These results indicate that the current degree of process orientation and the current IT infrastructure does not enable efficient use of quantitative process analysis and management tools like simulation.

In the second case the possibilities to develop generic hospital unit simulation models by building and validating a generic intensive care unit (ICU) model are explored. The results show that some of the modeling approaches described in literature cannot replicate the actual behavior observed in all studied ICUs. It is important to identify patient groups for different admission priorities, to account for over-utilizations in the model logic, and to discover and properly model dependencies in the input data. The research shows that it is possible to develop a generic ICU simulation model that could realistically describe the performance of different real ICUs in terms of occupancy, coverage and transfers.

The value of simulation modeling in health care management is examined in the third case through the development and use of a simulation model for optimal resource allocation and patient flow in a hospital operating department. The goal of the simulation modeling in this case was to identify bottlenecks in the patient flow and to try different alternatives for allocation of operating room capacity in order to increase the utilization of operating room resources. The final model was used to evaluate four different proposed changes to operating room time allocation.



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Linköping, May 2010

Krišjānis Šteins



## LIST OF PAPERS

This thesis consists of an introductory part and the following papers:

- I. Fryk, P., & Steins, K. (2010). A modern process perspective, process mapping, and simulation in health care. Opportunities and IT infrastructural needs. In *Proceedings of 2010 IEEE Workshop on Health Care Management (WHCM)*, Venice, Italy, Feb 18-20 2010. doi: 10.1109/WHCM.2010.5441276
- II. Steins, K., & Walther, S. (2010). *Developing a generic simulation model for planning of intensive care resource needs*. Unpublished manuscript.
- III. Steins, K., Persson, F., Holmer, M. (2010). Increasing Utilization in a Hospital Operating Department Using Simulation Modeling. Forthcoming in *Simulation* (Pre-published February 22, 2010). doi: 10.1177/0037549709359355



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# INTRODUCTION

*This compilation thesis consists of an introductory part and three separate papers. The aim of the introductory part is to provide the context for the research work that has been carried out and shortly describe each of the three papers and their individual contributions as well as summarize the research results. First, a short background to the thesis work is given, then the overall objectives of the research are formulated and methodological considerations discussed. Before the contributions of the research are presented, simulation methodology and its application area – health care and hospital patient flows – are described in brief. Finally, ideas for future research work are outlined.*

## 1. BACKGROUND

During the last couple of decades the health care sector has been under pressure since the demand for health services is increasing in an aging population while the funding of health care is not increasing at the same rate. The pressure is thus not on just making health care better from a medical point of view, i.e. developing better treatments for patients, but also on making the delivery of health care services more efficient. Accessibility, for instance, is a well known problem in Swedish health care and has lately been addressed by the government instituting a guaranteed medical care, where patients are guaranteed to get access to health care services in a certain number of days. There is a growing interest in applying tools and methods in health care management, which have been successfully applied in other service organizations and industries and have helped improve the planning and efficient use of resources while maintaining high quality of the delivered service or product.

Operations research methods, such as simulation and optimization, are also receiving this growing interest, although they are not new to health care. Operations research has been applied in health care since at least 1950s (Royston, 2009), i.e. almost since the beginnings of operations research as a civil discipline. Recently, however, there has been a growth of interest and applications of

operations research and simulation in health care, with the number of publications increasing significantly after 1990 (Brailsford et al., 2009). At the same time we can see a growing body of literature describing applications of simulation in different health care settings where there is little evidence on how the results of simulations are actually implemented (Fone et al., 2003) and what the value of using simulation in health care really is. Some authors (Brailsford, 2005; Harper & Pitt, 2004) have proposed possible reasons for this lack of reported implementation. In an international comparison (Brailsford et al., 2009) there are few documented studies of simulation applications in Swedish health care.

## **2. OBJECTIVES**

The overall purpose of this thesis is to investigate possibilities and requirements for using discrete-event simulation in analyzing and planning the use of hospital resources. The research area is the application of simulation in health care management and the main contribution of the research is in development and application of simulation methodology in planning of hospital resources.

The aim of the research is to increase the understanding of what is required in order to gain acceptance of simulation as a tool in hospital resource planning. Can standard solutions and standard simulation methodology work when applied to this particular setting? The research also aims to shed some light to why there are so few documented implementations and what is required in order to make simulation more widely adopted. The goal is also to look at the differences between developing generic or specific models, as well as the aspects of developing models of a single organizational unit and models that span across several hospital units or departments. Yet another set of contributions is related to specific cases described in the three research papers. These contributions are related to operating room allocation strategies, intensive care unit capacity planning and improvements in patient flow of emergency patients that require a radiology examination.

The question that might be raised here is whether there is something so unique and special about health care in general and planning of hospital resources in particular, that it requires special attention and dedicated research. Couldn't we just apply simulation methodology as it is and expect everything to work out just fine? In order to justify the special attention to simulation applications in health care, it must be pointed out that the common theme in all case studies carried out during this research has been the importance of validation and credibility of data

and models. In order for simulation to gain acceptance and credibility in health care community it has to be shown beyond any doubt, almost to a degree of scientific proof that it works both as a tool for learning and decision making in several different cases. And this concerns not only the models (the way we simplify reality) but also the data we use to drive them.

### **3. METHODOLOGICAL CONSIDERATIONS**

A case study approach was used to achieve the overall objectives of this thesis work. Such approach was chosen since other alternatives, such as survey or experimental methods are difficult if not impossible to apply in this situation. On one hand, experimental strategies cannot be used since it is very difficult to set up a controlled experiment in a hospital department without seriously disrupting the ongoing work and patient care. On the other hand, simulation is currently not used widely enough in Swedish health care in order to have a large enough sample to conduct a meaningful survey. Also, it is believed that the possibility to do a deeper investigation in a case study can provide additional insight, which is hard to capture in a survey.

When doing a case study research, it is important to select a “good” case study object. The selection can be done by either randomly picking a case out of several available options or by deliberately choosing a case that has larger potential in terms of providing answers to research questions in a reasonable period of time. Thus the selected cases do not have to be justified as being “typical” and aspects like availability and ease of access are at least equally important (Stake, 1995; Yin, 2009). The three cases in this thesis are similar in the sense that they all illustrate specialized care in hospitals and dissimilar in that the study objects are different departments in different hospitals. The common theme for all selected hospital departments – emergency and radiology, intensive care and operating rooms – is that the resources, both equipment and staff, are expensive and that these areas are often considered to be critical bottlenecks when looking at a patient flow in a hospital as a whole (Institute for Healthcare Improvement, 2003).

The research strategy is thus to apply discrete-event simulation in several different hospital departments while focusing on different aspects of simulation modeling and its application. The radiology department and emergency department study (Paper I: Fryk & Steins, 2010) looks at the prerequisites for successful and efficient application of discrete-event simulation and analyzes patient flow across the boundaries of two departments. The intensive care unit study (Paper II: Steins & Walther, 2010) investigates the development of a generic model for capacity

estimation at a single hospital department. The operating department study (Paper III: Steins, Persson & Holmer, 2010) investigates the development and use of a simulation model to find ways towards more effective usage of operating room resources in a hospital operating department. In this way selected cases taken together combine both unit and process/flow perspective, generic and specific model development, as well as include the whole simulation model lifecycle from preconditions to practical application and implementation of results.

Apart from the overall objectives of the thesis, each paper also has specific, case-related objectives and therefore requires using additional methodology, such as process mapping, data analysis and discrete-event simulation. The methodology used in each paper is briefly described below. For more detailed descriptions the reader is referred to each individual paper.

Paper I uses process mapping and data analysis for studying the degree of process orientation and conditions for effective use of simulation in the radiology department. The process model is developed together with the key actors at the hospital – nurses, physicians, administrative personnel, IT staff, and management. Historical data related to the process model is extracted from the hospital information systems and complemented with semi-structured qualitative interviews with health care professionals, on-site observations and secondary data sources. The research can be regarded as a traditional case study and is carried out as described and recommended by Yin (1999; 2009).

In Paper II discrete-event simulation was used for modeling an intensive care unit (ICU). Before simulation models can be used for decision support they have to be thoroughly validated. Model validation can be carried out in several different ways (Banks et al., 2010). First of all, the model must have face validity, i.e. it must produce results that would seem reasonable to the experts in the modeled system. Then all assumptions regarding simplifications, model logic and data must be carefully examined in order to ensure that all important aspects of the modeled system are included. And finally, validation of input-output transformations has to be done, most often by comparing model results to historical data. The simulation model described in Paper II was calibrated in several iterations with increased complexity in each new version. This was done to identify important patient and system characteristics that are necessary to include in the model in order to be able to represent the reality with sufficient accuracy when compared to historical data from several different ICUs. Such stepwise modifications and calibration of the simulation model is a common validation technique, described by Banks et al. (2010).

Discrete-event simulation was also used for analysis in Paper III. Simulation was chosen primarily because an operating department in a hospital can be seen as a queuing system where patients queue in order to utilize the operating resources. There is also a certain degree of stochastic behavior in the system since the operating times are unpredictable. Simulation offers the possibility to visualize new planning scenarios which was important in this case. Simulation also allows the dynamics of a system to be analyzed. In this case, the patient load varies from day to day creating a dynamic system. During the work several models were built with an increased level of complexity. To increase the credibility and acceptance of the model and its results in the organization, representatives of all operating specialties were involved in the model building process.

Since discrete-event simulation is very central to this thesis and all three papers the methodology for conducting discrete-event simulation studies will be described in greater detail in the following chapter.

#### **4. SIMULATION MODELING AS OPERATIONS RESEARCH METHOD**

Simulation modeling and analysis has been used for problem solving, prediction or analysis in many areas, e.g. in manufacturing, construction engineering, logistics and transportation, computer systems and network design, military applications and health care (Banks et al., 2010; Pidd, 1996). Simulation can be used for many purposes. Savén (1995) proposes twelve possible motives for using simulation, the main dimensions being decision-support, learning and communication.

It is important to note here that this thesis deals with a particular kind of simulation – computer-based simulation. Simulation in general is a very wide term and could also mean manual simulations, dedicated simulators and even role-plays. Computer-based simulation deals with building computer models (essentially computer programs) of the system of interest.

There are many definitions of computer-based simulation in the literature, below is one of them, used by Pidd (1998, p.3):

*“The basic principles are simple enough. The analyst builds a model of the system of interest, writes computer programs which embody the model and uses a computer to imitate the system’s behavior when subject to a variety of operating policies.”*

Another definition can be found in (Shannon, 1998, p.7):

Simulation is “... *the process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behavior of the system and /or evaluating various strategies for the operation of the system*”.

There are several types of computer-based simulation: discrete-event simulation, System Dynamics, Monte-Carlo simulation and agent-based simulation. As mentioned earlier, this thesis uses discrete-event simulation that implies the modeling of a system as it evolves over time by a representation in which system state variables change instantaneously at separate points of time (Law & Kelton, 2000). Discrete-event simulation models are dynamic, discrete and (most of the time) stochastic.

Discrete-event simulation models provide a risk-free environment for testing ideas, new policies, decision rules etc. They can handle dynamic and complex systems that involve uncertainty. Simulation experiments can be easily repeated and are often less costly than real experiments. On the other hand, simulation modeling requires special knowledge, both for model building as well as for analysis and interpretation of the results, and can be quite time consuming and expensive (Banks et al., 2010).

#### 4.1. SIMULATION METHODOLOGY

There are several alternative descriptions of simulation methodology in the literature, often outlined as a series of steps or a flowchart. The differences are not of a major character and the basic idea is the same. Brief descriptions of the most common steps in a “classical” discrete-event simulation study are presented below. The descriptions are based mainly on the simulation study steps given by Kelton et al. (2010) and Banks et al. (2010). It must be noted that a simulation project does not consist of a simple sequence of activities as outlined below. The different steps often must be revisited as simulation modeling is an iterative process.

**Formulating the objectives of the study.** Simulation is often seen as a problem-solving method. The first step in such a simulation project should therefore be to specify the problem to be solved, although sometimes the real problem itself becomes clear only during or after the simulation. From the problem statement one should establish objectives for the whole simulation study. This includes what questions the simulation model should answer. If the simulation model is intended to evaluate certain alternatives, these alternatives must be outlined and

the criteria for their evaluation established. After the objectives are specified, one must determine if simulation is the appropriate tool and if it is the best alternative among other possibilities. Even if there are simpler ways of finding solutions (e.g. using spreadsheets) the advantages and added value of using simulation should be taken into consideration.

**Model design.** Here the modeler first makes a conceptual model deciding on the scope and desired level of detail (McHaney, 1991). The flow of entities is often described by a process diagram and the rules and logic governing the flow are captured and documented. Conceptual modeling tasks of deciding on how to simplify the reality, what to include in the model and how to choose the right level of detail might be some of the most difficult tasks in simulation modeling. It takes skills which are hard to learn in a classroom, and is by some authors considered more an art or craft than science (Banks et al., 2010). The modeling process should begin with a simple model and then, only if found necessary, more detail should be added (Banks et al., 2010).

**Data collection and analysis.** This step is often interconnected with the model design and both are run in parallel. All model parameters are identified during this stage and relevant data about the system under study is collected according to the model scope and level of detail specified in the previous step. Data is usually gathered by querying databases, conducting interviews, examination of the existing documentation and direct observations and measurements. When collecting data from databases or other sources it must be carefully analyzed in order to discover and eliminate possible data errors (errors made while entering data into databases, biased data, missing values, etc.). A lot can be learned about the modeled system just through data analysis. Also, if data describing some of the parameters includes variability or randomness, a careful selection of appropriate probability distributions must be made. Ignoring the randomness can lead to incorrect model behavior, but this could also happen if the randomness is not modeled correctly. The simplest case of modeling randomness is when data for a parameter can be assumed independent and identically distributed (IID). If dependencies in data are discovered during data analysis or model validation then appropriate measures must be undertaken to include such dependencies in the model.

**Model translation.** During this step a working simulation model (essentially, a computer program) is created using general-purpose programming language or special simulation software – a simulation language or high-level simulator. The conceptual model must be translated to a specific language or environment, which

often restricts the modeler to the constructs that are built into that particular software. Therefore it is not always possible to smoothly transform the logical model to a computer model. The actual programming techniques depend very much on the language chosen. Usually, general-purpose languages require more time and effort for model building compared to simulation languages and high-level simulators.

**Verification and validation.** In simulation a distinction is often made between two types of model tests – verification and validation. Verification is the process of determining whether the simulation model performs as the model builder intended it to do. The model builder checks if the transformation from conceptual model to computer model is accurate by using debugging tools provided in the model development environment, examining both the internal logic of the model as well as the output and animation of the model. Validation is the process of determining whether the simulation model is an accurate representation of the system under study, given the purpose of the study. Validation can be performed by using a number of techniques. These include establishing face validity, comparing the output of a simulation model with historical data, thorough examination of model assumptions, extreme condition tests, sensitivity analysis, etc. (Sargent, 2007). Verification and validation is performed to prevent the occurrence of three major types of errors in simulation projects as defined by Balci (1998) – error of rejecting a valid model (Type I error), error of accepting an invalid model (Type II error) and error of solving the wrong problem (Type III error). Complete model validation is impossible and the model should not be judged as either absolutely correct or absolutely incorrect (Balci, 1998). Instead, the testing is done until there is sufficient confidence that the model produces acceptably accurate results.

**Experimentation.** This step involves designing and conducting experiments in order to fulfill the objectives of the study. Design of experiments (DOE) involves selecting the alternatives to be simulated and if the number of alternatives is large (many combinations of input parameter values) then statistical DOE techniques can be applied. Experimental setup also involves deciding on initial state conditions for the model, length of warm-up period, length of simulation run, and number of replications. It is recommended to consider experimental alternatives already during the model design, since it will to a large extent determine the model outputs. On the other hand, new experimental ideas are often generated during the stages of experimentation and analysis, which once more emphasizes the iterative nature of simulation modeling and analysis.

**Analysis of the results.** Most of the discrete-event simulation models are stochastic. Stochastic simulations, apart from having random input, produce output that is random too (Kelton et al., 2010). Because of this, statistical techniques are used for output analysis. Average values across a number of replications as well as confidence intervals are calculated for all significant output measures. The model is usually run for a sufficient number of replications in order to have confidence intervals that are narrow enough. Simulation modeling often involves more than just evaluating a single alternative. Output analysis also involves comparing the results from two or more experiments and selecting the “best” alternative.

**Implementation.** The final step in a simulation study consists of two activities – result presentation and implementation. The most common definition of implementation is when the recommendations and suggestions from the simulation study are applied in the real world. Pidd (1998) calls this a tangible product of simulation. This is also the type of implementation that most reviews would look for in a survey of simulation applications. Implementation might not occur directly after a simulation project, and often the results from the simulation are only one of many sources of information that forms the basis of a decision. But Pidd (1998) also talks about an intangible product – improved knowledge and insight, that can be generated throughout the simulation study. It is often hard to evaluate how such improved knowledge and insight is later on translated in changes in system or people’s behavior, which makes the process of assessing the value of the simulation study even more difficult.

#### 4.2. SIMULATION TOOLS

Simulation model building includes writing computer programs. Simulation models can be built by using special simulation software or general-purpose programming languages. Some of the modern, specialized, data driven simulators allow the user to simulate a system contained in a specific class of systems, for instance, manufacturing or health care, with little or no programming. The disadvantage of such tools is that they often are very limited as to their “standard” elements and configurations. At the other end of the simulation software spectrum we find general-purpose programming languages (Java, C++, Visual Basic, etc.) that give the model builder unlimited flexibility but usually require much more effort in model building, model testing and output analysis. There are a few tools, e.g. ARENA (Kelton et al., 2010), that try to combine the flexibility of programming languages with the ease of use of data driven simulators.

Regardless of the tool used, the model building concerns developing a piece of software and one could argue that the end result of the simulation study should not depend too much on the tool chosen. This is not entirely the case, if we consider not only the numerical result of the simulation study but the simulation project as a whole. Robinson (1994, p.14) states that:

*“If the wrong software is purchased the time required to complete a project may be greatly increased and, at an extreme, the project may not be possible at all”*

Some advice on choosing the appropriate simulation software is given by Robinson (1994) and Banks et al. (2010), but often it may be difficult to determine beforehand which characteristics of the available software that are most important for the particular project.

#### 4.3. SIMULATION IN PRACTICE

Simulation modeling is most often carried out in a form of a job contract (McHaney, 1991). Nevertheless, managerial aspects of simulation model development have attracted little attention of the research community. Pidd (1998) distinguishes the process and content of a simulation study, as well as separates problem solving from project management. The process of the simulation study concerns the way how it is planned, conducted and completed, while content concerns knowledge related to problem domain as well as simulation skills. As already mentioned, simulation modeling is often seen as a problem-solving approach. However, in practice it may not be enough just to solve the problem technically, it has also to be managed (or handled) organizationally. Here we approach an interesting question, i.e. how should we evaluate a simulation project – by its content, by process or by outcome, which is the product of both content and process. Pidd (1998) suggests that it is the impact on the organization by which a simulation project will most likely be judged, and not by the technical criteria. Therefore it becomes important for the simulation analyst to manage process and content, problems and projects – all simultaneously. In a similar manner, Robinson (2002) describes the quality of simulation as a relationship between content quality, process quality and outcome quality. The relative importance of each of the three concepts may vary from project to project, but some empirical findings by Robinson (2002) indicate that process quality may be substantially more important than content quality in cases where simulation is seen as a process of social change. The concept of simulation quality is important to understand as it has implications for the last step of a simulation study – implementation.

## 5. HEALTH CARE, PATIENT FLOWS AND SIMULATION

During the past years, the health care sector has been in a state of constant change where demand for health services is increasing and so are the costs. The demand is increasing both in quantity and also in quality, due to several reasons. One of the reasons for increase in quantity is an ageing population with increased amounts of chronically ill patients and patients having multiple diseases. Another reason – for increase in quality – is increased expectations of modern patients, many of whom are well educated and well informed about diseases and possible treatments and medications. New technologies and treatments have improved health care but not necessarily made it less expensive. On the contrary, costs of health care in many developed countries have been steadily increasing during the past 10-15 years, both in amounts per capita and in their relative share of the country's GDP. In Sweden the total health expenditure was down at 8.1% of GDP in 1995 and was up at 9.2% in 2002 (Glenngård et al., 2005). At the same time, the number of acute-care hospital beds have decreased from 24 973 in 1996 to 20 378 in 2002 and is currently one of the lowest per capita in Western Europe, while the number of physicians and nurses has increased during the same period both in absolute figures and per capita. The total output of the health care system seems to be more or less constant (Glenngård et al., 2005). In a report on future trends in health care financing Stockholm city council has calculated that in 2025 the costs will exceed revenues by somewhere between 17 percent in an optimistic scenario and 33 percent a pessimistic scenario (Stockholms läns landsting, 2009). This financial gap can be closed by working in three directions – increasing spending on health care, managing the demand and providing more health care for the money spent (Stockholms läns landsting, 2009). Examples of the work that can be done in the third direction are improved care processes and improved allocation of resources that match the demand.

In a European comparison Sweden is consistently ranked best when it comes to medical outcomes but is found among the bottom 5 out of 33 countries when it comes to waiting times with only Portugal and UK having lower scores (Björnberg et al., 2009). Accessibility problems might be considered as an adverse effect of trying to control the costs but the data (Björnberg et al., 2009) indicate that Sweden does not score higher in the total health care ranking adjusted for health expenditure compared to several other top ranked countries that do not have such low scores in waiting times, e.g. Netherlands, Denmark and Germany. Waiting times do not just affect the patient but can generate more work for the health care system as patient's condition might worsen and require more effort

later, thus increasing the load on the system further and probably further increasing average waiting times.

Keeping costs under control, maintaining excellent outcomes and at the same time improving access and minimizing waiting times is a challenging task for health care policy makers and professionals. In solving this task there is a growing need for effective methods of making better informed decisions in planning, managing and improving health care. According to Brandeau et al. (2004) the decisions to be made can be grouped in two broad areas:

1. *Health care planning and organizing* which deals with economics and structure of health care systems as well as other public policy issues.
2. *Health care delivery* which includes both clinical practice and operations management for health care delivery.

Operations management is responsible for making health care delivery both effective (positive health outcomes and patient satisfaction) and efficient (minimizing resource use). These two goals can be in potential conflict with each other as, for instance, improving health outcomes might also mean increased use of resources (Vissers & Beech, 2005a). The range of issues that operations management deals with spans from strategic decisions on which services are delivered to facility planning and design, to scheduling of individual patients. This is so even if we narrow down the application area from health care as a whole to hospitals only. This thesis deals with operations management, or more precisely with capacity planning of hospital resources.

In addition to the already mentioned issues of increased demand, rising costs and limited capacity, Williams (2006) mentions limits in technology and informatics as well as lack in industrial engineering tools and methods as key drivers to hospital capacity problems. It is suggested that one of the reasons for delays in health care delivery is inadequate hospital resource planning, which in turn can be explained by historical functional unit orientation, with misaligned capacities that do not necessarily match demand (Kosnik, 2006; Källum, 2008).

According to Hall et al. (2006), successful work in reducing delays depends on collaboration between administrative and clinical processes, ability to see health care as a system and find bottlenecks and system failures in patient flows.

Vissers and Beech (2005b) propose a logistic approach for planning and managing hospital resources and distinguish between unit logistics, chain logistics and

network logistics. A unit in a hospital is typically a department that has a well defined function and has resources allocated to it to carry out its function. For instance, the operating department's primary function is to carry out surgical operations and its resources include operating rooms, staff and equipment. Other examples of units are the radiology department and the intensive care unit. Unit logistics focuses on planning issues in a single unit and can be used for capacity management and efficiency analysis of the unit. A typical goal of unit logistics approach to planning would be to increase resource utilization and throughput of the unit. The disadvantage of the unit logistics approach is that it more or less ignores the fact that the unit itself and its resources are a part of a larger process or patient flow, and improved performance in one unit can lead to problems elsewhere in the flow. In defense of the unit logistics approach it can be said that if a unit can be identified as a bottleneck or constraint in the overall flow then it might be worthwhile to make sure that this unit operates at its near optimal capacity (compare to Theory of Constraints (Goldratt & Cox, 2004)). In chain logistics approach, a chain is defined as a sequence of activities that is required to deliver a particular health care service to the patient. As such it can involve several units that need to coordinate their efforts in order to deliver the service efficiently. The chain logistics approach focuses on the service level and typical performance measures would include total time to deliver a service, waiting times, value-added times, etc. The advantage of the chain logistics approach is obvious from the patient flow perspective but the disadvantage is that it often cannot measure resource use properly, as resources are still allocated to functional units, which can be involved in several chains simultaneously. The network logistics approach combines both unit and chain approaches. This approach makes it possible to evaluate the tradeoff between service level and resource utilization, and ideally it should include all or as many units and chains as possible in a hospital. Modeling and analysis become very complex and therefore applications of the network logistics approach are rare.

Closely related to the area of health care operations management are quality management, performance management, information management and operations research (Vissers & Beech, 2005a). Simulation modeling is one of the operations research methods that can support planning, managing and improving health care delivery in general and hospital patient flows in particular.

Simulation modeling in health care is not new and applications have existed since the early days of operations research and simulation. The three main advantages of simulation over alternative analysis methods are: i) the ability to deal with uncertainty, ii) the ability to handle complex systems without unnecessary

oversimplifications and iii) the ability to visually communicate the proposed solutions. Brailsford (2007) classifies health care models in three groups: 1) models of the human body (including biological, pharmacological and physiological models), 2) operational or tactical models that model flows of individual patients, and 3) strategic, system-wide models.

There have been a number of literature surveys on simulation modeling in health care (e.g. Wilson, 1981; Jun et al., 1999; Fone et al., 2003; Brailsford et al., 2009; Gunal & Pidd, 2010) that cover many aspects of health care simulation. The details of these surveys provide the reader with interesting examples of the multitude of simulation applications in health care. However, in this introduction we will focus on issues that are relevant to this thesis and that have been highlighted in abovementioned surveys, mainly concentrating on applications of discrete-event simulation to hospital resource planning (belonging to the second group of models as classified by Brailsford (2007) above).

In a survey published in the early 1980s (Wilson, 1981), a long time before simulation became widely available through powerful personal computers and graphical user interfaces, only 16 out of 200 simulation projects were found to be successful in terms of implementation of study results. According to this survey the implementation can be judged as successful using several criteria:

- recommendations from the simulation study are actually carried out;
- accuracy of the model predictions compared to effects observed in real system after implementation;
- magnitude of observed effects, which can be quantified as financial savings.

Few of the implemented projects (7 out of 16) reached the follow-up stage and three were able to calculate the financial savings. Wilson suggests that chances of implementation increase if there is a real decision-making situation, if the decision makers are actively involved in the project, data is available or is possible to collect in required amounts and quality. Wilson also concludes that health care seems to be a difficult application area for implementing operations research studies.

In a later survey by Jun et al. (1999), the focus was on discrete-event simulation applied to health care clinics with many examples of simulation models used for patient scheduling and routing as well as resource (room, bed, staff) scheduling and allocation. The survey found very few models of complex integrated systems

(compare to network logistics approach discussed above) as well as very few visually oriented models.

In a systematic review of actual use and value of simulation in health care by Fone et al. (2003), the conclusions were mainly the same as in previous surveys – a wide range of applications, including hospital organization, infectious diseases and screening but very few studies that allow to assess the value of simulation due to missing reports on implementation.

*“Despite the increasing numbers of quality papers published in medical or health services research journals we were unable to reach any conclusions on the value of modelling in health care because the evidence of implementation was so scant.”* (Fone et al., 2003, p.333)

In a more recent review Brailsford et al. (2009) state that not much has changed since Wilson’s study:

*“Overall levels of implementation are depressingly low and suggest that little has changed since previous review articles”* (Brailsford et al., 2009, p.137).

This review reports also on the geographical distribution of documented simulation and modeling applications in health care and concludes that the majority of published studies are concentrated to North America and Europe, with USA and UK dominating the publication arena. Also, the majority of papers are published after 1990 (Brailsford et al., 2009).

A review by Gunal and Pidd (2010) finds that most papers are too specific, solving specific problems in individual units (compare to the unit logistics approach above) and are difficult to generalize from. Also, they find that model reuse is very low, which might have its objective reasons since sometimes the very process of building a model gives a significant contribution to knowledge gained in a simulation study.

Reflecting on the reasons for the low number of implemented studies Brailsford (2005) suggests several potential barriers to simulation implementation in health care: organizational culture in health care, high costs of developing models, poor quality data, academics willing to publish the results too quickly and a demand for specific models for each particular unit.

It must be noted here that not all models are meant to be implemented. If the purpose of modeling is to learn, generate discussion or simply communicate ideas then “implementation” in the sense defined by Wilson (1981) is simply not

possible. Some operations research methods do not require a “client” and therefore have lower proportion of implemented studies. Brailsford et al. (2009) compare low rates of implementation in statistical methods to high rates in qualitative methods, which almost all require a client to interact with. Simulation can be used both with or without a client, therefore a mix of implemented and not implemented studies is reasonable.

When compared to other application areas, simulation in health care appears both having less visibility and a poor success rate, although the situation is not perfect in other areas either. In industry a survey of simulation users in Sweden (Eriksson, 2005) showed that 47% of the projects were judged as successful and 33% delivered answers that only confirmed what was already known. In a survey comparing simulation use in health care and defense sectors (Naseer et al., 2009) a much lower stakeholder engagement was found in health care (7.84% compared to 38.5%) which can explain the low rates of implementing simulation outcomes. According to the survey authors possible reasons for this are organizational structure, low level of competition, training culture on the systems management level and restrictions in data usage (Naseer et al., 2009). Royston (2009) states that operations research is not very visible to managers and clinicians and that it is partly related to lack of implementation.

Thus the challenge for the future still seems to be getting models implemented in the sense of implementation as a tangible product and being able to generalize from simulation studies (Brailsford, 2007).

## **6. RESEARCH SUMMARY AND CONTRIBUTIONS**

This thesis includes three papers and in this section the contributions of each paper along with the papers’ overall contribution to the fulfillment of research objectives are summarized. The papers describe three different cases so there is no overlap in terms of study object.

Paper I is entitled “A Modern Process Perspective, Process Mapping, and Simulation in Health Care. Opportunities and IT Infrastructural Needs” (Fryk & Steins, 2010) and is co-authored with Pontus Fryk. An earlier version of the paper is published in P. Fryk’s Ph.D. dissertation “Modern Perspectives on the Digital Economy. With Insights from the Health Care Sector” (Fryk, 2009). The version included in this thesis is published in the proceedings of 2010 IEEE Workshop on Health Care Management.

Paper I investigates the current stage of digitization and process orientation in hospital care as a prerequisite for efficient process simulation and analysis. The underlying hypothesis is that with an increased level of digitization, i.e. with more and more information and data available in digital form, together with a move from functionally oriented to process oriented organizations that focus on patient flows, it should be easier to overcome some of the barriers for implementing simulation modeling and analysis in health care organizations. The increased level of digitization should simplify the data collection and analysis which is one of the most problematic steps in health care simulation according to several researchers (Harper & Pitt, 2004; Brailsford, 2005). Increased process orientation in turn should lead to easier modeling of the whole patient flow across boundaries of functional units and departments.

The empirical case for the paper is the flow of emergency patients from the emergency department through the radiology department and back to the emergency department at a fairly large university hospital. One of the reasons for investigating this particular patient flow in terms of resources and time spent during different activities, is that the hospital has set a goal that 80% of all patients should leave the emergency department within four hours. It would therefore be fruitful to examine, map and analyze this process using a quantitative method like simulation. The patient flow was mapped during a number of meetings and interviews with hospital staff and all important activities and resources were identified. Data extracted from the information systems at both departments was analyzed in order to be able to quantify the parameters of the conceptual patient flow model and enable simulation analysis. Process mapping and subsequent data analysis revealed a process that was not very well defined and measured. Analysis also uncovered disparate information systems storing incompatible and fragmented data. The main conclusion from the study is that the current degree of process orientation and the current IT infrastructure is not enabling efficient use of quantitative process analysis and management tools such as simulation. This finding is confirmed in the results of a survey (Langabeer & Worthington, 2010) where more than 90% of respondents mentioned inadequacy of information systems as the main problem when using operations research methods in health care.

Paper II is entitled “Developing a generic simulation model for planning of intensive care resource needs” (Steins & Walther, 2010) and is co-authored with Sten Walther. It builds on earlier work on intensive care unit simulation and modeling (Steins et al., 2006). During this earlier work a couple of simulation models were developed for investigating the need of intensive care resources.

Since there are many similarities between intensive care units in Sweden and since there is a common database (Swedish Intensive Care Registry) that holds information about all patient visits including time durations and resource usage, it was decided to develop and validate a generic ICU simulation model that could later be used for capacity planning in any of the intensive care units in the country.

Intensive care is one of the critical elements in the hospital since resource shortage here can result in dire consequences for the patients as well as it can act as a bottleneck in patient flows involving emergency department and operating rooms. On the other hand, this is one of the most expensive hospital care forms. Therefore dimensioning of intensive care resources should be done accurately and taking into account the variability in the patient volumes and lengths of stay. Four ICUs in different hospitals were selected and data about patient visits and resource capacities was extracted from the database. The generic ICU model was developed using a stepwise modification and calibration approach in order to identify both system-wide and patient-related parameters and their values to obtain a match between model predictions and actual data on occupancy and coverage. The results from the validation and calibration process indicate that some of the modeling approaches described in literature and used in our earlier model versions cannot replicate the actual behavior observed in all four ICUs. It is important to identify patient groups for different admission priorities, to account for over-utilizations in the model logic, and to discover and properly model dependencies in the input data. The research shows that it is possible to develop a generic ICU simulation model that could realistically describe the performance of different real ICUs in terms of occupancy, coverage and transfers.

Paper III is entitled “Increasing Utilization in a Hospital Operating Department Using Simulation Modeling“ (Steins et al., 2010) and is co-authored with Fredrik Persson and Martin Holmer. It builds on previous work presented at 29th Congress of the Scandinavian Society of Anaesthesia and Intensive Care, SSAI 2007 (Steins & Holmer, 2007). The paper is accepted for publication in Simulation (Transactions of The Society for Modeling and Simulation International) and is pre-published online.

Paper III describes development and use of a simulation model for optimal resource allocation and patient flow in a hospital operating department. The goal of the simulation modeling was to identify bottlenecks in the patient flow and to try different alternatives for allocation of operating room capacity in order to increase the utilization of operating room resources. The simulation was

developed in several steps with increased complexity in each new model version. The data required to drive the model was extracted from the operating department information system and complemented with a number of interviews. The process depicted in the model included pre-operative care, all operating rooms and post-operative care carried out in the operating department. It also included logic for planning daily operation schedules, prioritizing and allocating both elective and emergency cases to available operating rooms. Each version of the simulation model was validated by examining and evaluating critical assumptions and by comparing model results against historical data. The operating council consisting of representatives from the operating department and all operating specialties was involved in model development, formulation of experimental alternatives and evaluation of the results. The final model was used to evaluate four different proposed changes to operating room time allocation. The results showed that a more equal resource allocation is possible to achieve in all four tested alternatives.

Simulation modeling is currently not even moderately used in analyzing patient flows and planning resources in Swedish hospitals. The three papers put together show possibilities as well as barriers for efficient use of quantitative methods such as simulation for the abovementioned purpose.

Paper I indicates that in certain situations there could be major problems with data required to drive the simulation model, meaning that extra efforts (i.e. manual data collection, time studies, etc.) are needed to obtain the necessary information, which in turn makes the simulation projects time consuming and validation of models difficult. In these situations it is hard to justify the use of simulation since it is unclear what the value of doing simulations will be compared to the effort required. Also, process thinking across functional units is still more a vision than reality. For instance, in the case described in paper I it is impossible to track the patient between the departments and to find out in the data when a patient actually has left the radiology department.

This leads us to the question if simulation is applied easier within a functional unit. Papers II and III deal with two such hospital units – ICU and operating department – both of them often regarded as critical links in the hospital-wide patient flows. Since both units also represent a significant share of total expenses at a hospital efficient use of resources becomes an important issue.

One of the barriers for wider use of simulation in health care according to Brailsford (2005) is that there are too few generic models. Generic models can

both require much less effort when applied in new situations and can also gain acceptance easier if there is a good history in using that particular model elsewhere. Paper II describes the development of such a model where we have good quality data and a seemingly simple system, yet it is not a trivial task to develop a model that could faithfully describe several different ICUs. Nevertheless, a validated generic model using the same database that almost all intensive care units in the country are connected to has great prospects of actual usage in the future.

An example of site-specific model developed with implementation in mind is described in paper III. This was the first encounter of simulation at the operating department and the whole journey got a good start. The potential of simulation as a visual tool for testing and communicating different changes in the organization was recognized early. It was believed that simulation models could provide more objective grounds for discussions about potential outcomes of proposed changes. Since simulation was new to the operating department the study had a classic setup with a simpler pilot study and a more elaborated follow-up study. All scenarios tested in the model have a potential for implementation, but at the time of writing the paper III none of the scenarios were actually implemented, for a number of different reasons. Some of the planned changes were postponed due to financial reasons, some were part of a larger investigation and yet some involved changes in the whole hospital organization which was outside of the scope of the study. Now, months later, at the time of writing this summary, a version of first scenario is being implemented and will be followed up later (see section on future research). The challenge in evaluating such implementation is that reality keeps changing and an actual implementation in real life can depend on so many other factors that it becomes hard (if not impossible) to “scientifically” isolate the effect of the simulation model.

The greatest challenges regarding modeling and simulation aspects have been data problems (paper I), discovering and modeling dependencies among model parameters (paper II) and modeling planning logic of human planners that schedule the cases in operating rooms (paper III). The set-up for operating room schedule planning in paper III, which is in fact a simulation model inside a model, only without the stochastic element, is one of the distinctive contributions of this research to the field of simulation modeling. Another contribution, from paper II, is the way to model the delay until arrival of the next patient as a function of current occupancy.

The process orientation in hospitals is not mature enough to be able to easily apply the chain logistics approach (Vissers & Beech, 2005b) to simulation in hospitals. This might be one of the reasons of low usage of simulation modeling even though individual, unit oriented models can demonstrate high degree of validity. Validation of both data and model logic has been a central and important part in all three studies and is considered a key factor for the success of simulation applications in health care.

## **7. FUTURE RESEARCH**

The walk along all three paths charted in this work and documented in the three papers should be continued in order to further substantiate and refine the answers to the research objectives outlined earlier. Future work in all three directions – developing an inter-departmental patient flow model, developing a generic model for ICU resource use estimation and developing and using a simulation model for optimal resource allocation in an operating department – will provide a more detailed and comprehensive picture on the possibilities and requirements for using simulation in hospital resource planning. The continued work will hopefully show more clearly what the real value of simulating patient flows is, where the simulation gives the most “return on investment”, where it is easiest to apply, what data requirements there are, etc.

Work has already begun on developing a simulation model along the defined process in paper I. Interviews are used as information source for some of the missing data. Some of the missing timestamps will be omitted and new ones have been discovered. This of course means being at risk of using the data that is available and not what is really required.

The ICU model (paper II) is going to be elaborated more to include workload (instead of beds) as a measure of resource need which is important for planning purposes. The model should also be tested in real life situations to predict occupancy levels and coverage, for instance, in cases where structural changes are made in hospitals.

A modified version of the model described in paper III is currently being used to simulate the reallocation of operating room resources in order to match the capacity to actual demand. The suggested reallocation will then be implemented in reality and followed up on a regular basis. Also, it is important to look at alternative methods for management and planning of hospital resources.

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