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# RESOURCE OPTIMIZATION IN A DANISH HOSPITAL USING DISCRETE-EVENT SIMULATION

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## Preface - Prefazione

Col presente progetto, svolto in collaborazione con l'Università Tecnica della Danimarca (DTU) , il futuro Pronto Soccorso del Bisebjerg Hospital viene simulato tramite l'utilizzo del software di simulazione agli eventi discreti *Arena Simulation Software* by Rockwell.

Inizialmente, il problema viene contestualizzato sottolineando gli ambiti e sottolineando come la simulazione possa essere utilizzata nell'analisi di sistemi logistici.

I sistemi produttivi logistici hanno attualmente raggiunto un grande livello di complessità e sofisticazione sia dal punto di vista tecnico sia da quello organizzativo; inoltre a questo si affianca, spesso, un grande impegno di risorse economiche.

Per questa ragione, nel momento della progettazione dei sistemi produttivi (ed in particolare modo di quelli logistici), sta diventando sempre più importante una fase di verifica della fattibilità tecnico-economica che anticipi la realizzazione pratica dell'impiantistica. Oltre a ciò, anche nella successiva fase di gestione del sistema realizzato, la forte competitività impone una continua ricerca del miglioramento.

La simulazione, assieme ad altri metodi matematici, rappresenta un potente strumento per condurre i sopracitati studi [1].

Nel proseguo dell'elaborato i diversi metodi di *System-Analysis* vengono elencati e discussi, soffermandosi sui pregi e difetti degli stessi, enfatizzando l'importanza della simulazione.

Successivamente l'attenzione viene posta sull'analisi delle diverse tipologie di simulazione esistenti, in relazione ai sistemi che vengono presi in considerazione; una metodologia di simulazione viene poi presentata, elencando gli step consigliati per sviluppare ed implementare il modello di simulazione nel miglior modo possibile.

Ulteriori considerazioni vengono, dunque, sviluppate in merito al ruolo della simulazione nel campo del *Health-care*.

Proseguendo, l'attenzione viene spostata sui software di simulazione ed, in particolare, su *Arena* (software implementato nel presente progetto): le caratteristiche del software vengono presentate e descritte, assieme agli *add-on* di *Arena* utilizzati nel corso della simulazione: *Input Analyzer*, *Process Analyzer*, *Output Analyzer* and *OptQuest*.

Nel capitolo successivo il sistema reale è preso in esame: inizialmente il Bispebjerg Hosptial viene brevemente descritto assieme al *Bispebjerg Construction Project*, progetto tramite il quale l'ospedale verrà modernizzato ed espanso.

La fase iniziale del piano sopracitato consiste nel progetto di rinnovo dell' *Emergency Department*; in seguito le caratteristiche dello stesso vengono approfonditamente descritte con lo scopo di analizzarne il funzionamento.

Il modello di simulazione viene poi presentato, accompagnato dall' *activity diagram*; i dati in Input vengono esposti ed analizzati: un primo studio è stato effettuato riguardo la distribuzione di arrivo dei pazienti (*Arrival rates*) su base oraria con lo scopo di stabilire quale di queste si adatti nel migliore dei modi al modello.

In funzione dei due migliori *Arrival Rates* vengono, successivamente, analizzati il numero di infermiere nel reparto *Triage* e il numero di letti nel reparto *48ore* ottimali in grado di garantire il corretto funzionamento dell'intero pronto soccorso e consentire tempi di servizio e attesa prestabiliti dalle regole vigenti.

Per concludere, i risultati ottenuti dal modello di simulazione vengono presentati e discussi; tramite la comparazione con i risultati aspettati, il modello viene convalidato e differenti scenari vengono poi analizzati.

# Introduction

In the present project, the Emergency Department (ED) of the future Bispebjerg Hospital will be simulated with the use of Arena Simulation Software by Rockwell.

Initially, a brief preface has been made to introduce where and how simulation can be used, in order to achieve default goals in the study of a selected system: starting with contextualizing the problem into the Logistics' world, the increasing importance of Logistics in the actual production systems is described. Furthermore different tools of system-analysis are listed and for each of them a brief description has been made, explaining their advantages and disadvantages, and for which type of analysis they can be used in order to emphasize the benefits of simulation.

Afterwards, an entire chapter is dedicated to simulation: different kind of simulations are listed according to different type of systems; a simulation methodology is discussed in order to explain the recommended steps to develop the simulation model and perform it in the right way. Moreover, other considerations are made regarding the role of simulation in the important field of health-care.

Subsequently the attention is moved on simulation software and particularly on Arena Simulation Software: the software is generally described along with its main characteristics and the tools (add-on) used in the current simulation (Input Analyzer, Process Analyzer, Output Analyzer and OptQuest).

Starting from chapter 4, the real system is taken into account.

Firstly the Bispebjerg Hospital will be presented within the *Bispebjerg Construction Project*, with which the whole Hospital will be renovated and enlarged.

Secondly, the attention is moved on the Emergency Department: the *ED Project* will be presented, its function and characteristics will be explained in order to describe how the system behaves. Furthermore the provided Input data will be shown and analyzed. Then, the simulation model will be presented within the activity diagram and two initial arrival rates will be determined.

Consequently, the needed number of triage nurses will be studied for the different arrival rates trying to estimate which one of them better approximates the real system; the chosen one, will be later used in the test model for further analysis.

Moreover, the needed number of beds will be estimated and the results of the final solution will be presented.

Finally, its robustness will be validated through the comparison with the expected results and different scenarios will be performed.



# Chapter 1

## Logistics and System-analysis methods

### 1.1 Logistics

The term *Logistics* comes from French *logistique* or *loger*, which means "allocate"; its definition can be explained in several ways according to the context in which it's considered.

According to the Council of Logistics Management, logistics "contains the integrated planning, control, realization, and monitoring of all internal and network-wide material-, part- and product flow including the necessary information flow in industrial and trading companies along the complete value-added chain (and product life cycle) for the purpose of conforming to customer requirements".

Logistics can be either defined as the process of planning, implementing, and controlling the effective and efficient flow of goods and services from the point of origin to the point of consumption.

The *International Society of Logistics* (Sole) [2] made a classification in order to better explain the role of Logistics in different fields:

- **Business logistics** = (incorporates all industry sectors) aims to manage the fruition of project life cycles (flow of products), supply chains and resultant efficiency;
- **Bulk logistics** = regards management and handling of large amounts of loose materials, generally commodities (such as oil, coal, grain, etc.);

- **Project logistics** = which concerns the management and co-ordination of planning and realization of complex systems (such as large-scale and infrastructure, power plants, etc.);
- **RAM logistics** = which relates to the management of high-tech products (airlines with planes and helicopters or other complex systems) which are essential for reliability, availability and maintainability;
- **Reverse logistics** = is the process of planning, implementing and monitoring the efficiency of raw materials, semi-finished goods, finished goods and related information flows from the point of recovery (or consumption), to the origin point, with the aim to regain value from products that have exhausted their life cycle.

As far as the business management is concerned, in the last years a more modern and correct term has been built, defining the logistics as *integrated logistics*.

The concept of integrated logistics was synthesized in a precise way in definition proposed by the Council of Logistics Management in 1986, according to which it represents "the process by means of which to plan, implement and control the flow of raw materials, semi-finished and finished goods, and related information flows, from the place of origin to place of consumption, in order to make it as efficient as possible and complies with the requirements of the customers".

This definition perfectly explains how logistics plays an increasingly important role in the modern days and its purpose becomes substantially that of governing all stages of the productive process, even outside the company, according to a systemic view. This means that systems and their process flow have to be improve and optimize.

In the next section different ways to analyze systems are listed.

## 1.2 Systems Analysis

A system is "a composite of people, products, and processes that provide a capability to satisfy stated needs. A complete system includes the facilities, equipment, materials, services, data, skilled personnel and techniques required to achieve, provide and sustain system effectiveness." [3]

As said in the previous section, Logistics' goal is to study the process flow of *systems* in order to achieve a better efficiency and optimize them. There are several ways to study a system, as shown in *Figure 1.1*.

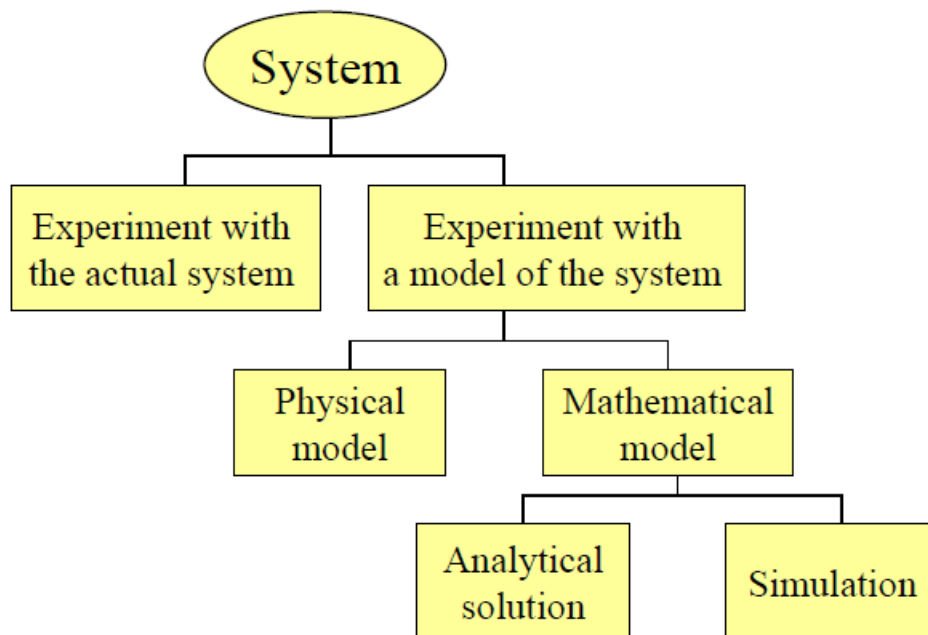


Figure 1.1: *Different ways to study a system.*

The first distinction in the system analysis can be made between working with the actual system or a modeled one. This difference is linked with the complexity of the system that have to be analyzed: if the problems are not that complex or interconnected to each other, the easiest way to study them is working directly with the actual system; furthermore, real world systems are often too complex for analytic models and often too expensive to experiment with directly.

According to those reasons it's necessary to work with a model of the system, able to represent (with a certain value of simplification) the real behavior of the chosen system. The model can be either physical or mathematical but, for the same reasons explained

above (complexity, difficulty and costs), the mathematical one is usually preferred. Once decided to work with the mathematical model, two different approaches can be taken into account

- Analytical solution
- Simulation

The analytical solution consists in the creation of a mathematical model and in its solution using mathematical analysis (probability, statistics, differential equations); its aim is to represent the most closely as possible a system.

A mathematical model is built with the aim to provide predictions on a future state of a phenomenon, generally, the model describes the likely evolution of a phenomenon or of a physical system on the basis of initial data by returning final output.

The efficacy of the model can be measured by comparing the output data with the observed result of the observed system.

The whole next chapter is focused on Simulation.

# Chapter 2

## Simulation

Simulation can be defined in different ways according to the field in which it is applied; generally speaking, *Business Dictionary* [5] defines simulation as follow: "acting out or mimicking an actual or probable real life condition, event, or situation to find a cause of a past occurrence (such as an accident), or to forecast future effects (outcomes) of assumed circumstances or factors. Whereas simulations are very useful tools that allow experimentation without exposure to risk, they are gross simplifications of the reality because they include only a few of the real-world factors, and are only as good as their underlying assumptions".

In a more technical way it has been defined as a "transposition in terms of logical-mathematical and procedural a conceptual model of reality, the conceptual model can be defined as the set of processes that take place in the system and evaluated which together makes it possible to understand the logic of operation of the system itself".

Or: "imitation of the operation of the real-world process or system over time. Simulation involves the generation of an artificial history of the system and the observation of that artificial history is draw inferences concerning the operating characteristics of the real system that is represent." [4]

A key advantage of simulation modeling is its capability of modeling entire system and complex interrelationship; all important interactions among components of the system can be accounted for within the model. As explained through the previous definitions, simulation is not a perfect tool and it has got some defects in its implementation. Despite all, the most important advantages in using simulation, compared with the other tools described previously are shown in *Figure 2.1*:

Benefits over real life experimentation	Benefits over mathematical modeling	Managerial benefits includes
Cost, repeatability, control over the time base, legality and safety	dynamic and transient effects, non-standard distributions, interaction of random events	fosters creative attitudes, promotes total solutions, makes people think, communicating good ideas

Figure 2.1: *Benefits of simulation.*

The purposes of simulation can be manifold: to respond to question "what if ...", comparing two or more systems, optimize some parameters, identify the critical points of the system, to predict the future behavior, etc..

Different sort of simulations can be listed according to the type of systems that is going to be simulated. In order to explain this, systems (and therefore simulations) may be classified according to different aspects, regarding on how they evolve over time and the randomness of the events they're going through.

In a first place systems may be divided in Stochastic and Deterministic:

- *Stochastic* when randomness is an important component of the system;
- *Deterministic* : system in which no random behavior are involved in the development of future states of the system.

Moreover it can be considered Static or Dynamic;

- *Dynamic* whether it changes with respect to time;
- *Static*: a system whose characteristics are not a function of time.

As far as a dynamic system is taken into account, continuous or discrete ones could be evaluated according to how they evolve over time:

- *Continuous* if the state of the system changes continuously;
- *Discrete* when changes occur at discrete points in time.

Since the goal of this report is to study and simulate the Emergency Department of the Bispebjerg Hospital, few considerations can be made about this type of system in order to explain what kind of simulation is needed in the present case.

Few considerations can be made analyzing the arrival rate of the incoming patients at the ED:

- The arrival rate has a completely random behavior; it can't be predicted (meaning knowing exactly at what time patients are entering the system). The managers of the Hospital could just estimate when they will have peaks, analyzing previous arrival rates from different time frames. Accordingly to this, the system can be considered *stochastic*.
- The patients flow through the system makes it changes every time a patient enter the system; for this reason the system can be classified as *dynamic* (it changes with respect to time) and *discrete* (it doesn't change continuously but at discrete points of time).

In the next sections discrete-event simulation is taken into account and the peculiarities of simulation in the health-care are listed and discussed; moreover a methodology to analyze a problem creating the right simulation-model is explained.

## 2.1 Discrete-event Simulation

Discrete-event simulation is an important tool for the modeling of complex system.

It is used to represent manufacturing, transportation and service system in a computer program for the purpose of performing experiments. Representation of the system via a computer program enables the testing of engineering design changes without disruption to the system being modeled.

Simulation modeling involves elements of system modeling, computer programming, probability and statistic, and engineering design”. [9]

This simulation type is used for a wide range of applications, summarized in the following categories:

- Facilities Planning: designing a new facility.
- Obtaining the best use of current facilities: potential solutions could be tested and identified.
- Developing methods of control: more than just physical equipment, for example experimenting with different control-logic as MRPII or Kanban.
- Material handling: experiments can be performed to control the flow of material to find for example bottlenecks.
- Examining the logistics of change: to minimize interruptions, simulation can be used to examine the logistics of changes.
- Company modeling: high level model showing for example the flows of resources and information between sites.
- Operational planning: simulation can be used in day-to-day planning and scheduling.
- Training operation staff: supervisors and operators are trained in the operation of the facility.

Particularly in the current case-study, discrete-event simulation will be used to analyze the flows of resources and entities through the model.

Regarding the role of simulation in the health-care field, numerous studies can be found in literature; in the next section, advantages and disadvantages of simulation in health-care are discussed in order to empathize the reason why simulation is widely used in that field.



## 2.2 Simulation in Health Care

Nowadays, hospitals undergo massive changes. The changes in demography (e.g. ageing), in economy (work organization, European harmonization) and in the society (unemployment, precariousness) destabilize the way hospitals usually work and their economic balance.

To face these problems, the social protection system has to turn over a new leaf. Besides, the rise in competition in Europe compels private and public hospitals to modernize themselves (e.g. equipment) and to produce more (the number of patients, duration of the stay at hospital,). On these challenges depends the hospital efficiency, in other words their survival.

The objective that hospital managers must reach is to optimise its production by meeting the customers demands. It is translated into a rational use of resources (human, financial and material resources) and the maximization of the customers satisfaction, who contributes to the enterprises durability. This ambition is really hard to achieve since :

- Hospitals have to meet a demand that depends on the seasons;
- Material and human means used to meet this demand are not always the same for a given pathology (which defines the kind of service to be offered) and are limited;
- Although health care procedures do exist, the notion of technical data is not as obvious as for the manufacturing industry.

Conversely to the industrial sector, hospitals can't freely determine their tariffs but have to guarantee appropriate and high quality health care at the lowest cost. Controlling the cost price is the only thing to be concerned with and is thus a necessity. In other words, hospitals can be considered as a service enterprise offering several kinds of products that are subjected to constraints resulting from limited human and material resources, and which is trying to offer better health care and to spend less money at the same time. The main feature of this enterprise is the difficulty in quantifying and formalising its processes.

In the field of hospital management, the planning of material and human resources is achieved on the basis of health care expectations and by taking the heavy constraints

of the personnel (e.g. a reduced number of practitioners, personnel's varied timetables, timetables that are specific to the practitioners etc.) into consideration. This process aims at the improvement of the quality criteria (time patients have to wait, number of patients waiting before being treated etc.) as well as the minimization of cost criteria (supplementary work hours, equipment usage cost). This prediction-based management must be flexible, so that we can include the hazardous nature of hospital activities. It can be compared with the preparation of an organized planning for any industries' production.

Hence, simulation is of the utmost importance even considering the hospital facility, differently from what it might be thought in the first place. [6]

"Software has been increasingly adapted to health care through enhanced visualization and modeling. Frequent problems are patient flow, staffing, works schedules, facility capacities and design, admission/scheduling, appointments, logistics and planning. Health care problems are especially complicated by the fact that "people serve people", meaning people are both the customer and the supply." [7].

As presented in "Improving patient flow in a hospital emergency department" [8], because of the variability caused by unscheduled arrivals, simulation is widely used for analyzing many different approaches to ED process improvement.

Stephen D. Roberts in "Tutorial on the simulation of health-care systems" [7], depth explains qualities and advantages that makes simulation an optimal tool in health-care systems :

- *Variability*: very little in health care is certain. In fact, it would be more accurate to claim that everything is stochastic. Simulation can incorporate variability through its handling of random variables and probabilities outcomes.
- *Complexity*: health care is a complex system of human behavior. Doctors, nurses pharmacists, and technicians all interact to provide patient care. And the patient is often left to negotiate the maze of health care options, all the way from finding out where the lab is in the hospital to deciding whether their loved one is to receive that operation.

Human behavior defies casual modeling. Nonetheless simulation can provide descriptive models of what transpires. It is a level of complexity that is often beyond the flow in a network of queues (although a network of queues may be a good starting point). Simulation modelers can build models of the system they see, as opposed to the system someone idealizes.

- *Assumptions*: All modeling tools make certain assumptions about the real system. It may be that the arrivals are Markov or that objective function is linear. Simulation has the advantage of requiring fewer assumptions by the modeler. Thus the modeler is free to model the system as it exists rather than modeling it in an idealized form. However, all models have assumptions, so it is incumbent on the modeler to be clear about the assumptions, especially since health care is so sensitive to behavioral issues. Ignoring the assumptions about actual behavior can invalidate an otherwise great simulation.
- *Ease of Use*: ease of use contributes to the application of simulation. Although the use of simulation requires that the modeler work closely with the stakeholders and develop a simulation that is acceptable to a variety of perspectives, the ease with which models can be built is a tribute to the value of simulation languages. While knowing one simulation language is generally sufficient, knowing and using more than one simulation language enhances the modeling alternatives.
- *What if*: One of the most attractive features of simulation is its experimental nature. People in health care like experiments and understand them. Experiments with the simulation model are a natural approach to the use of simulation. It also gives different people a chance to inject their ideas about how the system might be improved. This "what if" analysis often inspires a full discussion of trade-offs among objectives.
- *Perspectives*: if the modeler is successful in providing a useful simulation language, the experience and results will bring a new perspective to the organization. In particular, health care workers, who usually have no prior simulation exposure, often being to see how patient flow, resource use, scheduling and other relationships affect the quality of patient care. This "system perspective" introduces a broader concern with potential changes and can enhance decision-making by the stakeholders. This change in perspective may trump the actual benefits of the simulation results.
- *Acceptance*: Simulation models tend to be accepted in the health care environment because they often provide a visual interpretation on the model, they make few assumptions about the real system, and can provide experimental results. If the various stakeholders are incorporated into the model-building process, the acceptability is further enhanced.
- *Lean/Six sigma*: Simulation is increasingly seen as a tool that enhances a lean/six

sigma program in health care. Incorporating simulation into a general performance improvement program enhances the performance improvement potential and provides an opportunity to address many health care delivery issues not captured by a simulation.

Despite the increased importance of simulation in the health-care field, there are still some issues that make its implementation a not so easy task; the most important factors can be resumed as follow:

- *The Decision-Making Structure in Health Care*: many professional disciplines can be seen inside Health-care; since decisions are made by consensus and not through authority, a comprehensive simulation should satisfy a number of parts.

It's important to note that not all the stakeholders are equal in spite of a growing sharing of authority; doctors are often the most important part and model implementation needs to pay special attention to their reaction.

- *Simulation Models are Personal*: simulation model can be made arbitrarily complex; there is usually no agreement on the "level of detail" sufficient to be included in the model. Individual simulation modelers may have surprisingly different models for the same problem.

- *Multiple Goals and Stakeholder Interests*: the fact that there are different health care system goals such as costs, access and quality naturally produce confusion as to which goal is the most important or which goals are achieved.

Because different stakeholders have different frames of reference and different point of view, the simulation model results may be lost among the various interests.

- *Not the Important Problem*: one of the most insidious problems that face the simulation modeler is the potential over-use (misuse) of simulation.

Simulation is a convenient modeling tool with the capacity to model complex system. Yet simulation remains only a tool and not a solution. So it is not uncommon to see a simulation used when a simple spreadsheet or even a set of simple calculation would suffice.

The first step in deciding to use a simulation is to determine that a simulation is needed. It's hard enough to do a simulation, but to do one when it's not required is a waste of time. Remember that the third statistical error is "solving the wrong problem".

- *Educate the Stakeholder*: the oft-heard recommendation to involve the stakeholders early in the simulation study is truer in health care system than in other areas of application.

Generally, the health-care stakeholders have no prior knowledge of simulation and must be educated as to its potential use. If this education doesn't begin at the genesis of simulation study, then the simulation modeler risks a substantial loss of interest in the final results and recommendations.

- *Lack of Validation*: one of the most difficult steps in a simulation project is the validation, namely making sure that the model reflects the essence of the real-world being modeled. Validation is especially critical in health-care, since input data is often hard to obtain in a health care setting and assumptions can make the model invalid.
- *The Data Challenge*: in spite of its need to report various health outcomes to government and insurance organizations, there is a very little data on the operational aspects of health care. Even data on simple questions like how does radiology schedule its patients, what is the length of stay in a Post-Anesthesia Recovery Area have unbelievable complicated answers.

Getting data to "fit" a statistical distribution on the amount of time a doctor spends seeing a patient in an outpatient clinic will likely be non-existent. Therefore, it is likely a simulation modeler in health-care will engage in an extensive data collection effort as a part of simulation model development.

Because so much data will need to be collected, a "rough-cut" model is needed before engaging the detailed data collection, so that only important data is collected.

- *Rough-Cut Data in Health Care*: a rough-cut model developed early in the simulation life cycle can help to focus the simulation project and to avoid intrusive data collection of unnecessary data. Rough-cut simulations play an especially important role in health care since data is often such a challenge. To simplify the effort, the modeler can solicit from the various members of the organization the data needed in the form of estimates.

The easiest is to ask for a minimum, a mode, and a maximum (a mode or most likely value is preferred to a mean, since a mean is a computed value). These estimates can be converted into a Pert or Beta distribution for input to the simulation. Generally speaking, a simulation based on such information usually performs quite well and can give early results to engage stakeholders.

- *Patient Arrivals*: random arrivals in a health care facility will not be time-homogeneous. Instead, the arrival process will change depending on the time of day, the day of the week, and sometimes the month.
- *Multi-objective Performance Criteria*: it is difficult to easily define the general performance characteristics in health-care. They often depend on the individual institution or decision. Most operational simulations provide information about queuing, cycle times, and resource utilization.

In health care the cycle times and queuing may need to be subdivided according to patient acuity or patient type. Resource utilization may need to be obtained for individuals as well as groups. In health care, space is often a critical resource. Exam rooms, recovery beds, ward beds, operating rooms, etc. all require special attention and most often need to be included in the simulation model. Layout of space is a complicating factor and changes in layout are quite difficult for existing facilities.

After describing advantages and disadvantages in applying simulation as a procedure to system-analysis, in the next section a methodology to perform a concrete and useful simulation model is described.

## 2.3 Simulation Methodology

In this paragraph an overview of the steps needed during the creation and the implementation of a simulation model is presented.

This methodology can be resume within 6 steps:

1. Define the problem
2. Establish measures of performance for evaluation
3. Generate alternative solutions
4. Rank alternative solutions
5. Evaluate and iterate as necessary
6. Execute and evaluate the solution

This is called DEGREE problem-solving methodology (**D**efine the problem, **E**stablish measures of performance for evaluation, **G**enerate alternative solutions, **R**ank alternative solutions, **E**valuate and iterate as necessary and **E**xecute and evaluate the solution) and it represent an easy and powerful tool for simulation to problem-solving.

The first step makes sure that you're solving the right problem, the second one helps to ensure that you're focusing on the problem in the right way, the next two steps refer to the evaluation of multiple solutions in order to develop the right one. Step 5 is focused on the iterations:the analyst evaluates how the process is proceeding and allows for iteration (the problem-solving process can be repeated until the desired degree of modeling fidelity has been achieved). The last step indicates that, if possible, the solution should be executed, implementing the decisions; finally the project benefits should be checked if they're obtained or not.

However, as far as simulation is concerned, the DEGREE approach must be modified to consider how simulation will interact with the overall problem-solving process.

*Figure 2.2* represents all the steps for applying simulation in greater details:

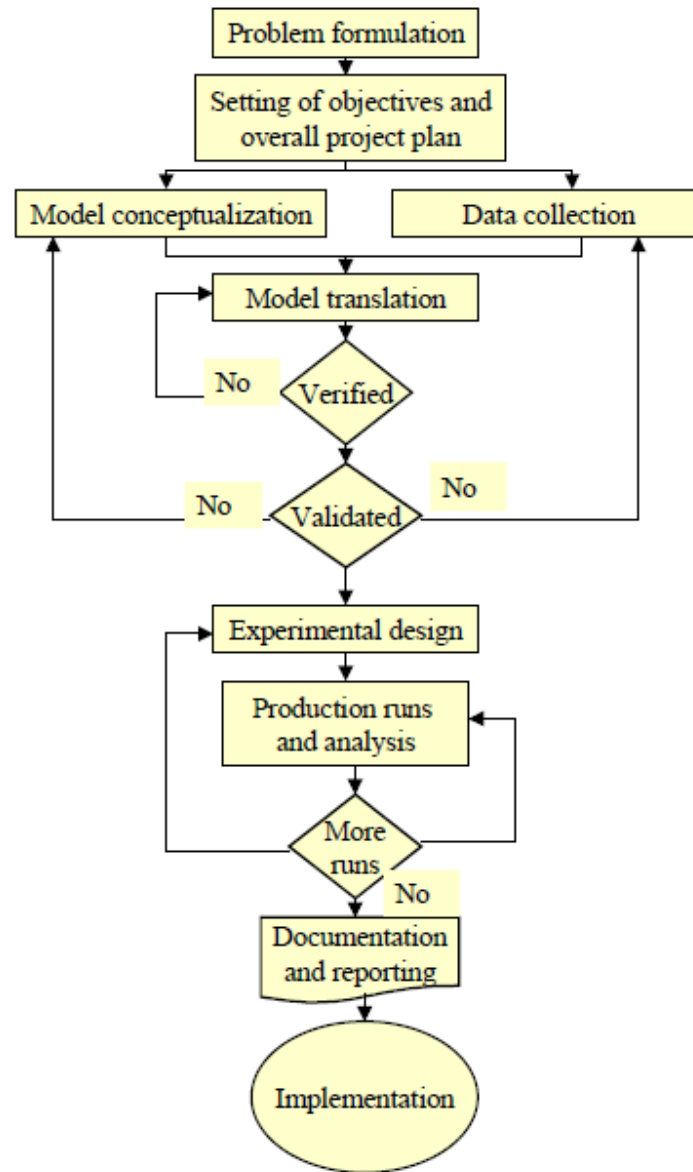


Figure 2.2: *Simulation Methodology*.

This graph can be discussed according to a 6 steps list:

1. **Problem Formulation:** it captures the essence of the first two steps in the DEGREE process; it consists of five primary activities (Defining the problem, Defining the system, Establishing performance metrics, Building conceptual models, Documenting modeling assumptions).

The main purpose of this phase is to discuss and accurately represent the problem; all the made assumption during the modeling process must be documented in order to examine their effect on the model during the verification, validation



and experimental analysis steps of the methodology.

The problem definition should include a detailed descriptions of the objectives of the study, the desired outputs from the model, and the types of scenarios to be examined or decisions to be made.

With the second activities, the system is accurately analyzed, defining its boundaries, making sure that the scope of the project is well understood.

The third activity consists in the definition of the required performance measures of the model; to meaningfully compare alternative scenarios, objective and measurable metrics describing the performance of the system are necessary. The focus should be placed on the performance measures that are considered to be the most important to system decision-makers and tied directly to the objectives of the simulation study.

Subsequently, conceptual models of the system are strongly recommended (diagrams, flow-chart, etc.) before using software to implement the model. The purpose of conceptual modeling tools is to convey a more detailed system description so that the model may be translated into a computer representation. General descriptions help to highlight the areas and processes of the system that the model will simulate.

Some relevant diagramming constructs include *Context Diagram* (which assists in conveying the general system description; it's a pictorial representation of the system ), *Activity Diagram* ( pictorial representation of the process for an entity and its interaction with resources while in the system), *Software engineering diagrams* ( flow-chart, database diagrams, IDEF diagrams, UML (unified modeling language) diagrams, and state charts are useful in documenting complex modeling situations.

These techniques assist development and coding efforts by focusing attention on describing, and thus understanding, the elements in the system.

2. **Simulation model building:** during the simulation model-building phase, alternative system design configurations are developed based on the previously conceptual models. Additional project planning is also performed to yield specifications for the equipment, resources and timing required for the development of the simulation models.

Within the context of a simulation project this process includes:

- *Input data preparation:* input data are analyzed to determine the nature of

the data and to determine further data collection needs.

- *Model translation*: the act of implementing the model in computer code, including timing and general procedures and the translation of the conceptual models into computer simulation program representation.
- *Verification*: verification of the computer simulation model is performed to determine whether the program performs as intended. Verification consists in model debugging to locate errors in the code. Errors of particular importance include improper flow control or entity creation, failure to release resources and incorrectly observed statistic.

Model debugging also includes scenario repetition using identical random number seeds, "stressing" the model through a sensitivity analysis to ensure compliance with anticipated behavior, and testing of individual models in the simulation code.

- *Validation*: validation is performed to determine whether the simulation model adequately represents the real system. The simulation model is shown to personnel associated with the system in question. Additionally, further observation of the system are performed to ensure model validity with respect to the actual system performance. A simple technique is to compare the output of the simulation model to the output of the real system and to analyze whether there is a significant difference between the two.

3. **Experimental design and analysis**: after the modeler is confident that his model has been verified and validated to suit its purpose, the model can be performed to investigate the goals, the objective of the project, and determining length of simulation, number of replications, etc.. .

4. **Evaluate and iterate**: executing the simulation to generate the desired data and to perform sensitivity analysis, drawing inferences from the data generated by the simulation runs. Reporting the results and findings.

During this step of the process, any quantitative models developed during the previous steps are exercised.

Using the simulation model's statistical results, alternative scenarios should then be analyzed and ranked. If the modeler is satisfied by achieving his objectives, documentation and implementation should be performed; if not, iterations are necessary in order to determine whether any additional data, experimentation, or analysis are needed to achieve modeling objectives.

5. **Documentation:** this step consists in documenting the model and its use. Good documentation should consist of at least two parts: a technical manual, which can be used by the same analyst or by other analysts, and a user manual.

A technical manual is very useful when the project has to be modified, and it can be a very important contribution to software re-usability and portability. In addition to good model development documentation, often the simulation model will be used by non-analyst; in this situation, a good user manual for how to use and exercise the model is imperative.

The user manual is a product for the user who may not be an expert in programming or simulation issues; therefore, clearness and simplicity should be its main characteristic.

6. **Implementation:** the implementation is the last step of this procedure; in this phase, the recommended solutions should be implemented and the analyst should follow through the installation and integration of the solutions. After the implementation, the project should be evaluated as to whether the proposed solution met the intended objectives.

The next chapter contains an overview of one of the most popular and powerful simulation software commercially available: Arena by Rockwell.



# Chapter 3

## Arena Simulation Software

### 3.1 Arena Simulation Software



”Arena software enables you to bring the power of modeling and simulation to your business. It is designed for analyzing the impact of changes involving significant and complex redesigns associated with supply chain, manufacturing, processes, logistics, distribution, warehousing and service systems”. [9]

Typical scenarios include:

- Detailed analysis of any type of manufacturing system, including material-handling components;
- Analysis of complex customer service and customer management systems;
- Analysis if global supply chains that include warehousing, transportation and logistics systems;
- Predicting system performance based on key metrics such as costs, throughput, cycle times and utilization;
- Identifying process bottlenecks such as queue build ups and over-utilization of resources;

- Planning staff, equipment or material requirements.

With Arena it's possible to:

- **Model** processes to define, document and communicate.
- **Simulate** the future performance of the system to understand complex relationship and identify opportunities of improvements.
- **Visualize** operations with dynamic animation graphics
- **Analyze** how the system will perform in its "as-is" configuration and hundred myriad of possible "to-be" alternatives so that you can confidently choose the best way to run a business.

In *Figure 3.1* the Arena Modeling environment is shown in order to explain the basic knowledge of the software.

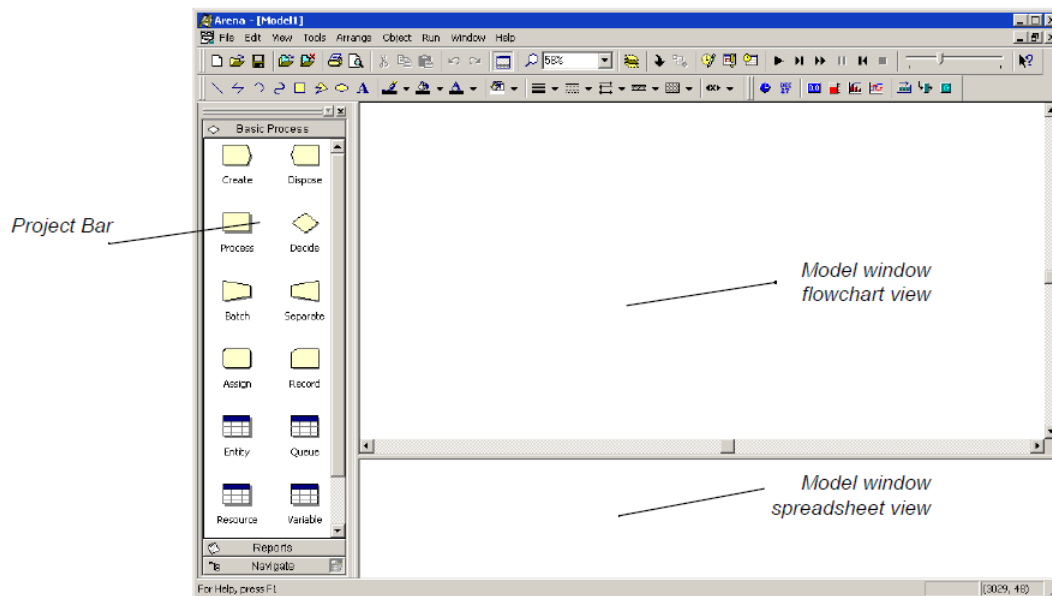


Figure 3.1: *Arena Interface.*

To model your process in Arena, the workspace is divided into three main regions; the *project bar* hosts panel with the primary types of objects a modeler will work with:

- **Basic Process, Advance Process and Advance Transfer panels:** contain the modeling shapes, called *modules*, needed to define the processes.

- **Report panel:** contains the reports that are available for displaying results of simulation runs.
- **Navigate panel:** allows the modeler to display different views of the model, including navigating through hierarchical submodels and displaying a model thumbnail view.

In the model window, there are two main regions. The *flowchart view* will contain all of your model graphics, including the process flowchart, animation and other drawing elements.

On the bottom there's the *spreadsheet view* which displays model data, such as time, costs and other parameters. The *Arena User's Guide* clearly explains all the modules, possible operations and characteristics of the software [10].

It is important to recognize that simulation allows you to reproduce a real-world system and it is primarily a decision support tool; as far as a solution of a problem is needed, other software have to be taken into account.

In the next sections a brief description of all the add-on included in the Arena Package used in this project is given.

### 3.1.1 Arena Input Analyzer

Arena's Input Analyzer is a powerful tool that allows you to analyze different type of data; it is used to fit probability distributions to data and/or to evaluate the fit.

Input Analyzer performs two goodness-of-fit tests for any distribution you attempt to fit: the chisquared test and the Kolmogorov-Smirnov test. For each test it prints the *p-value*, telling you how well the distribution fits your data.

As it can be seen in *Figure 3.2* , Input Analyzer also shows you how you would enter the distribution in an Arena simulation model; for example :  $-0,5 + \text{WEIB}(8.66, 2.78)$ .

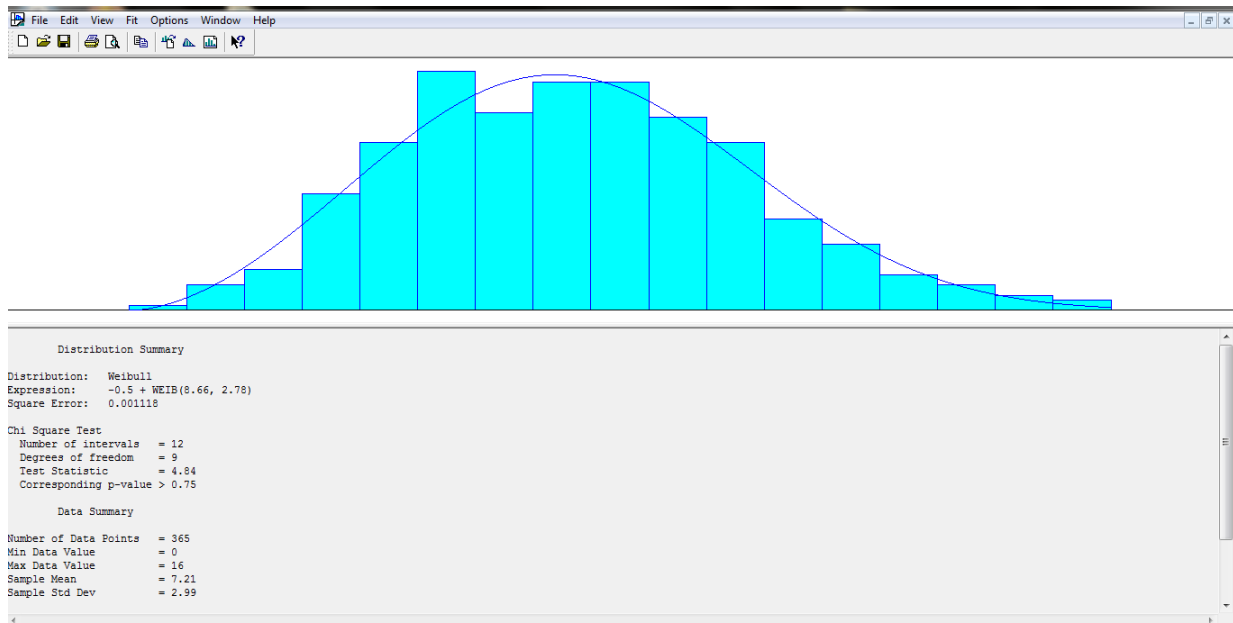


Figure 3.2: *Arena Input Analyzer*.

### 3.1.2 Arena Output Analyzer

*Arena Output Analyzer* is used for some of the plotting that it facilitates; it's true usefulness is the ability to easily construct an auto-correlation plot and other kind of plots. An auto-correlation plot allows dependence in the data to be quickly examined. Creating Histograms, Process analyzer will give as results all the needed data to discuss, read and understand the plot. An Histogram Summary can be seen in *Figure 6.2.3*.



### 3.1.3 Arena Process Analyzer

The *Arena Process Analyzer* is a tool that supports parametric analysis of Arena models by allowing the modeler to create, run and compare simulated scenarios, and thus observe the effect of prescribed responses.[9]

The term *parametric analysis* refers to the activities of running a model multiple times with a different set of input parameters for each run, and then comparing the resultant performance measures. Its purpose is to understand the impact of parameters changes on system behavior (sensitivity analysis), often in the process of seeking the optimal configuration (parameter set) with respect to one or more performance measures or combination thereof.

In *Process Analyzer* input parameters are called *controls*, and the resultant performances values are called *responses*. Controls may consist of variables and resources capacities, while responses include both variables and statistics. In *Figure 3.3*, the Process Analyzer Environment is shown:

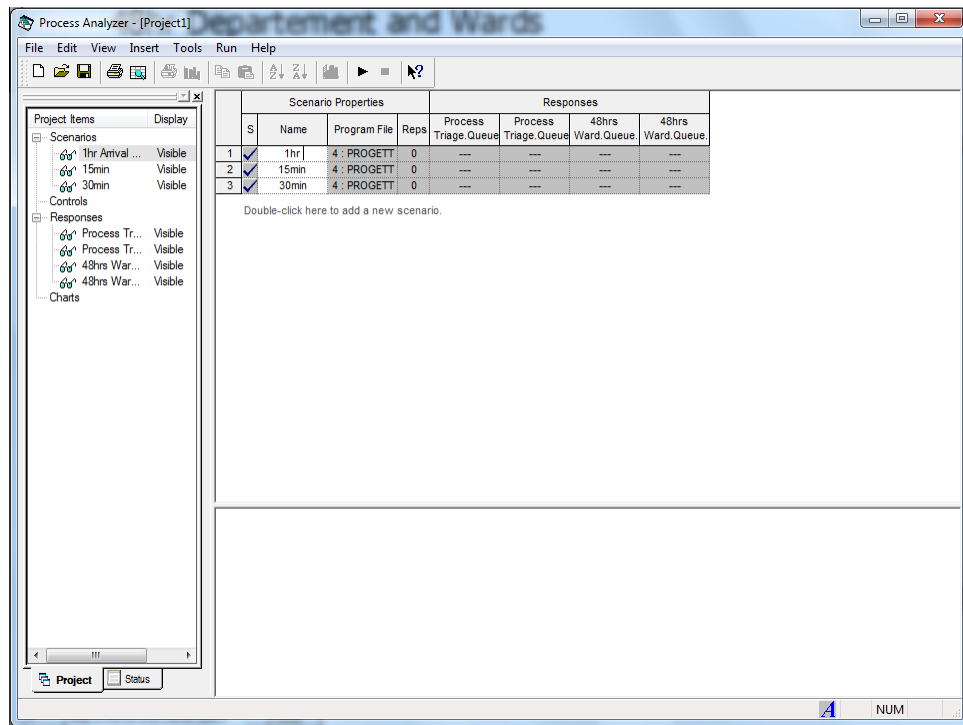


Figure 3.3: *Arena Process Analyzer*.

### 3.1.4 OptQuest



OptQuest is one of the products developed by OptTek. An optimization software and services company, OptTek is the leading provider of optimization software to companies that employ simulation [12].

OptTek's software uses methods that integrate state-of-the-art metaheuristic procedures, including Tabu Search, Neural Networks, Scatter Search, and Linear/Integer Programming, into a single composite method.

The state-of-the-art optimization technology embedded in OptQuest can be used directly by analysts to search for optimal solutions to complex business and engineering problems. User-written applications can communicate with OptQuest Engine via a flexible and intuitive object model.

OptQuest Engine uses metaheuristic, mathematical optimization, and neural network components to guide the search for best solutions to decision and planning problems of all types. The user-written application tells OptQuest Engine the quality of each solution generated during the search, by calling an evaluator (such as an objective function) that can take any form. For example, the evaluator may simulate a complex system to determine its behavior based on a proposed solution.

#### **OptQuest for Arena**

As written above "simulation is primarily a decision support tool and does not directly seek optimum solutions"; this is what OptQuest is made for: "OptQuest enhances the analysis capabilities of Arena by allowing you to search for optimal solutions within your simulation models".[13]

Without this powerful tool, the optimal solution must be searched using heuristic or ad hoc fashion: run a simulation with a set of decision variables, analyze the results,

change the set-up (one or more variables) and re-run the simulation until satisfactory results are obtained. Of course this process could be very tedious and a loss of time even for small models, and it often causes mistake in changing the variables from one simulation to the next.

OptQuest overcomes this problem, automatically searching for the best solution within your Arena's model: "It's ultimate goal is to find the solution that optimizes (maxims or minimizes) the value of the model's objective, and it's designed to find solutions that satisfy a wide variety of constraints that you may define".

An *optimization model* has three major elements: controls, constraints and an objective, which are described in *Figure 3.4*.

Controls	Are either Arena Variables or Resources that can be meaningfully manipulated to affect the performance of a simulated system. The optimization model is formulated in terms of the selected controls. The values of the controls are changed before each simulation is performed.
Constraints	A constraint defines a relationships among controls and/or responses. <u>OptQuest</u> differentiates between linear and non-linear constraints. Linear constraints describe a linear relationship between controls; a non-linear constraints contains a non-linear expression
Objective	Is a mathematical response or an expression used to represent the model's objective (e.g. minimizing or maximizing queues) in terms of statistics collected in the Arena model.

Figure 3.4: *OptQuest Controls, Constraints and Objective.*

Conceptually, an optimization model might resemble the *Figure 3.5*.

When OptQuest is launched , it checks the Arena model and loads information from the model, including the defined controls and responses, into its own database. The user then proceeds to define the optimization problem using OptQuest's explorer interface.

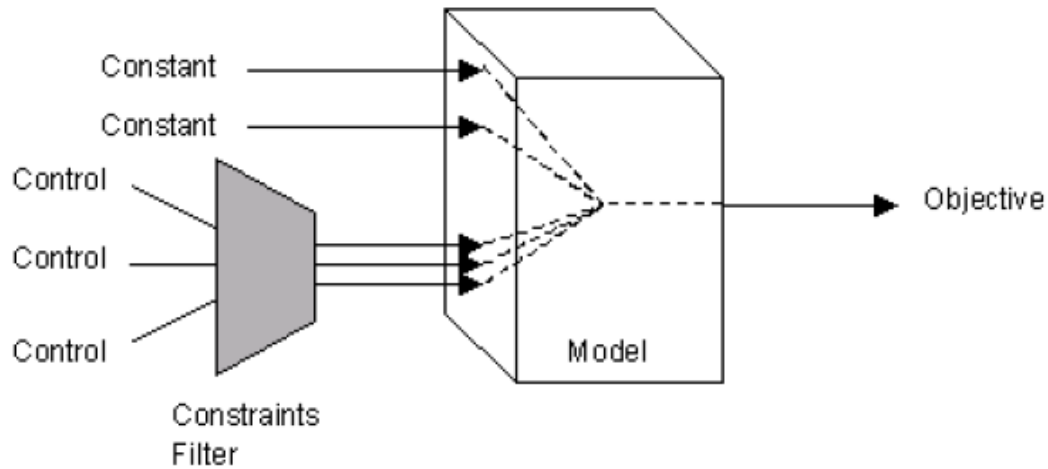


Figure 3.5: *How OptQuest works.*

The optimization procedure uses the outputs from the simulation model to evaluate the inputs to the model; analyzing this evaluation and previous evaluations, the optimization procedure selects a new set of input values.

It performs a special non-monotonic search where the successfully generated inputs produce varying evaluations, not all of them improving, but which over time provide a highly efficient path to the best solutions.

The optimization is stopped when a criterion is satisfied; usually after a number of simulation or when the objective values stops to improve. Once OptQuest is ended, the Arena's set-up remains unaffected and it returns to the original default value. In this way, while the simulation model can change and evolve to incorporate additional elements, the optimization routines remain the same.

Therefore, OptQuest is an optimizer that makes it possible to separate successfully the optimization solution procedure from the simulation model. With this design adaption of meta-heuristic methods, it is possible to create a model of your system that includes as many elements as necessary to represent the "real thing" accurately.

While the simulation model can change and evolve to incorporate additional elements, the optimization routines remain the same.

Hence, there is complete separation of the model that represents the system and the procedure that solves optimization problems defined within this model.

Figure 3.6 explain this concept:

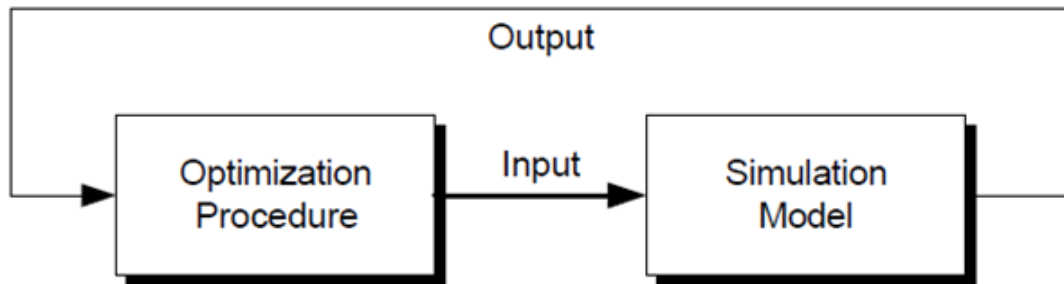


Figure 3.6: *OptQuest Methodology.*

The interface between the two programs is implemented using the Arena COM object model, which is also available to Arena users through VBA, Visual Basic and other development tools.



# Chapter 4

## Bispebjerg Hospital



In this chapter the Bispebjerg Hospital will be briefly described in order to contextualize the goal of the current project.

Bispebjerg Hospital is one of the hospitals in the Capital Region of Denmark; along with a number of other hospitals and the University of Copenhagen (the Faculty of Health Sciences), Bispebjerg Hospital forms part of the Copenhagen University Hospital.

Bispebjerg Hospital was built in 1913, and today it is the workplace for 3,000 employees. It is a large hospital with many different specialties, complex patient cases and a diversified group of patients. It serves as community hospital for the inhabitants in large parts of Copenhagen and will henceforward be main hospital for the planning area called "Byen".

Bispebjerg Hospital functions as a modern city hospital for 400,000 citizens from the Municipality of Frederiksberg and the larger part of the Municipality of Copenhagen and, at the same time, has to provide special services for an even larger population.

It is situated on the hill Bispebjerg Bakke like a green oasis in the city. From the buildings there is a fine view over the city and the unique green gardens, which were laid out in 1913 when the hospital was built. The hospital is constructed with the original pavilions and some newer buildings that are all connected underground through a large tunnel system.

In *Figure 4.1* an overview of the actual Hospital can be seen.

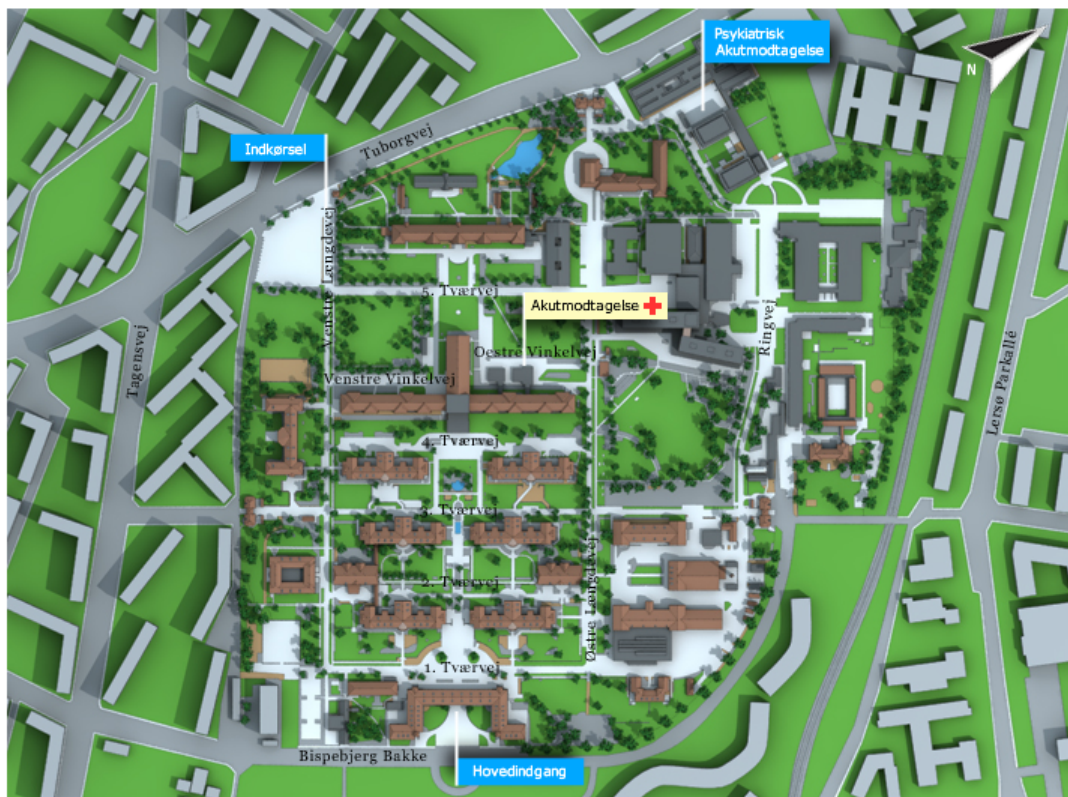


Figure 4.1: *Bispebjerg Hospital.*

Bispebjerg Hospital lives up to international standards for quality development and safety. Since 2002 the hospital has been accredited by the American organization Joint Commission, a non-profit organization established to improve the safety and quality in the care and treatment offered by hospitals internationally. [15]



## 4.1 The Bispebjerg Construction Project

In 2012 the Bispebjerg Hospital has started the so called *Construction Project*, with which they are going to enlarge, modernize and improve the Hospital. The details of project can be seen if *Figure 4.2*.

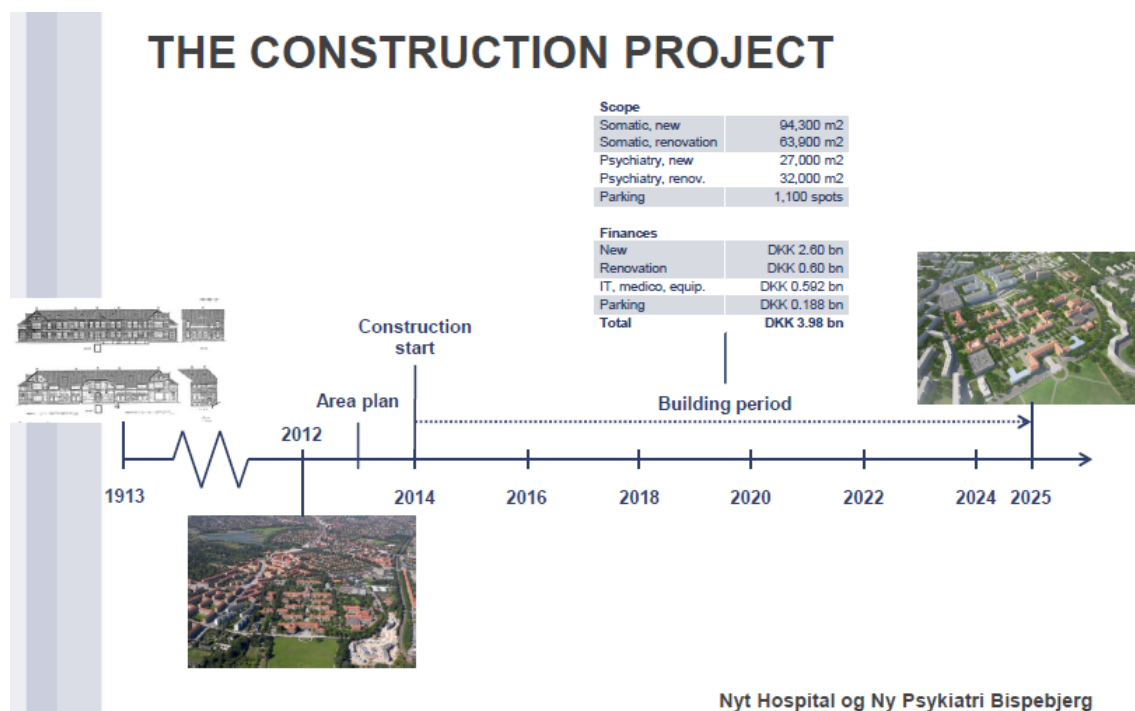


Figure 4.2: *The Construction Project*.

Moreover, there will be a merger between Frederiksberg and Bispebjerg Hospital. It brings together the best cultural aspects of the two hospitals, which ensures collaboration filled with presence and with focus on high-quality patient care, professionalism, patient involvement and warmth.

The project also brings together the Psychiatric Centre Copenhagen and Children's Psychiatric Centre Bispebjerg on the hospital grounds of Bispebjerg Bakke. This ensures highly specialized psychiatric treatment as well as psychiatric research, which ultimately will become one of the main psychiatric research facilities in Denmark.

The project consists of both renovations of existing buildings as well as new building. This is completed throughout a 10 to 12 year period, during which time the hospital is operating at full capacity. All of these aspects cause the construction process significant challenges.

In *Figure 4.3* can be seen the current map of the hospital, meanwhile after the re-build the Hospital could look like *Figure 4.4*:

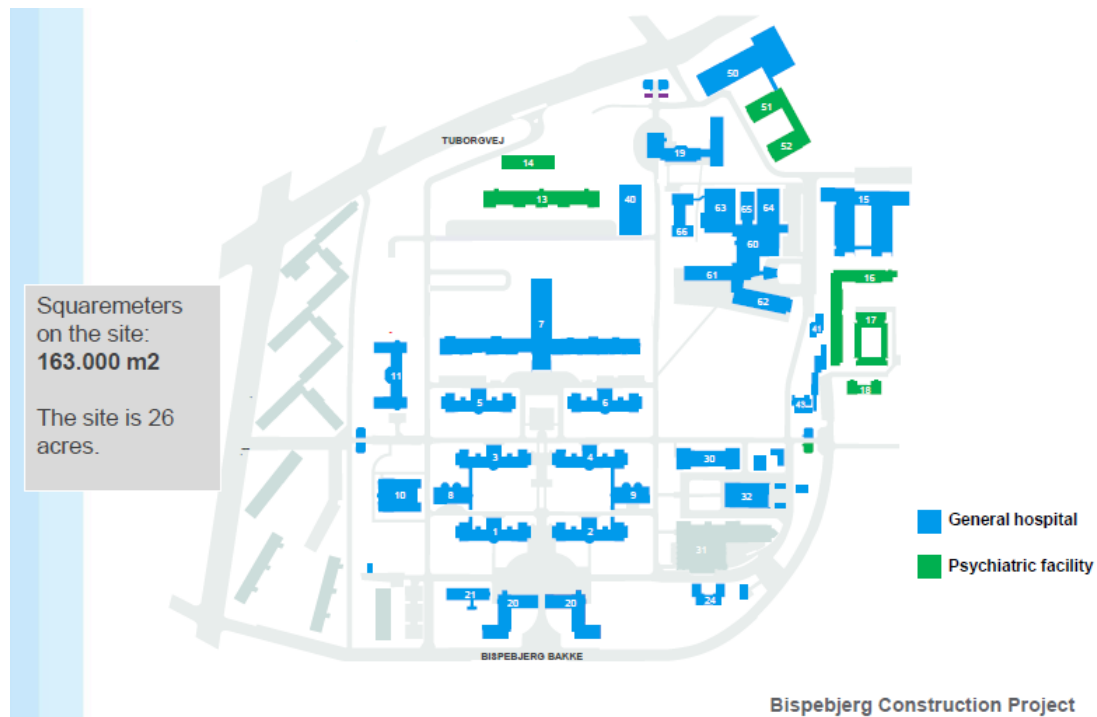


Figure 4.3: *Bispebjerg Hospital nowadays.*

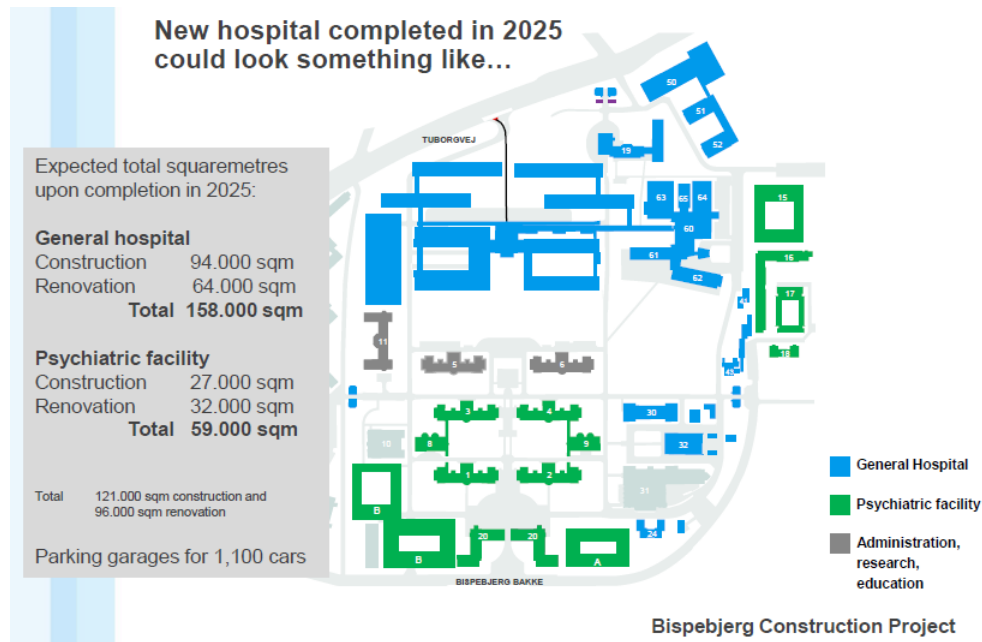


Figure 4.4: *Bispebjerg Hospital in 2025.*

#### 4.1.1 The Emergency Department Project

The first step in the *Construction Project* is the modernization of the Emergency Department.

Nowadays the ED serves around 45000 patients per year: it is made by several entry points converging in a Reception that acts as the first step in the treatment process; after the patients are divided according to the triage process, they are served in small equipped rooms where they are served.

The concept behind the new Emergency Department is to increase its importance and efficiency, moving some of the operations that usually belong to the departments, to the ED. This can be made by the creation of one ward inside the ED called: it will be called *48hr Ward* where patients will be able to stay no longer than 48 hours. The goal of this particular project is to simulate the ED estimating how many nurses and beds are needed in the above mentioned Department in order to serve with a good efficiency the incoming patients. In *Figure 4.5* all the steps of the Methodology explained in 2.3 are revisited in order to understand how the Hospital and DTU have worked together to achieve the fixed goals.

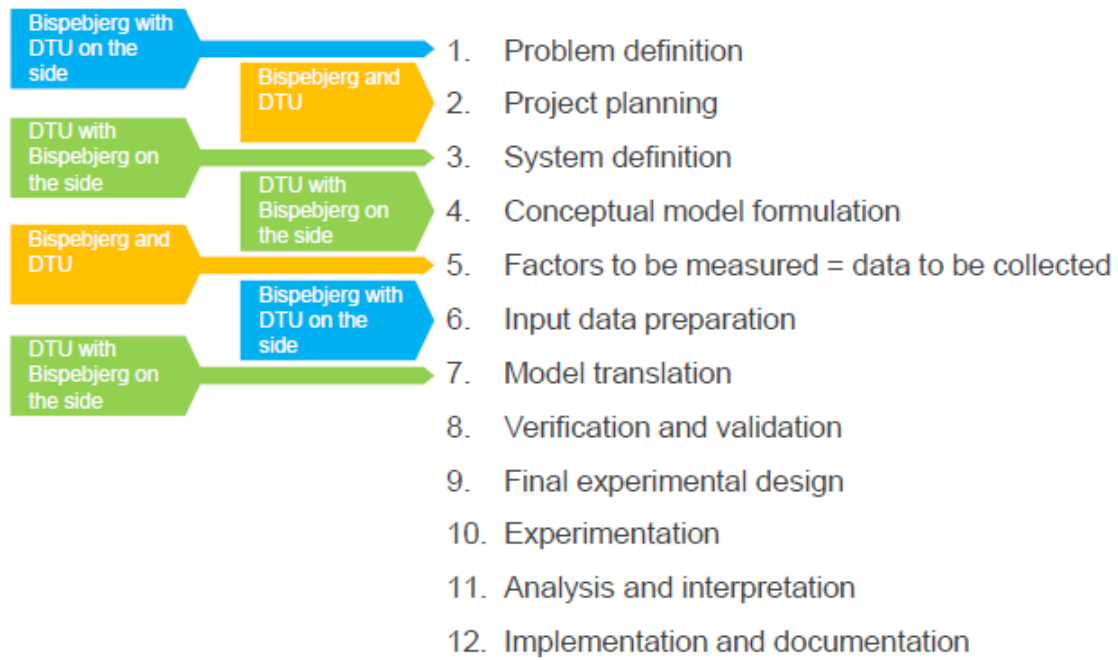


Figure 4.5: *Methodology.*

In the next section the ED is described, creating the basis for the development of the simulation.

## 4.2 ED's Description

Patients arrive at the ED either by ambulance or on their own. Firstly they enter the reception where they give their details and health card. Then, they arrive to the triage, where the severity of their health problem is assessed with the use of the Triage system ; the patients are divided according to a 5-level classification system which categorizes patients by acuity and resource needs (Eitel et al. 2003), either as *Red*, *Orange*, *Yellow*, *Green* or *Blue* ones, based on a form filled by the triage nurse, which is presented in Figure 4.6.

1 Red Livstruende 0 min	2 Orange Haster 15 min	3 Gul Haster mindre 60 min	4 Grøn Haster ikke 180 min	5 Blå 240 min		
Ikke frie luftveje Inspiratorisk stridor				Uden vitalparametre		
SpO <sub>2</sub> < 90% med O <sub>2</sub> SpO <sub>2</sub> < 80% uden O <sub>2</sub> RF > 35 eller < 8	SpO <sub>2</sub> < 95% med O <sub>2</sub> SpO <sub>2</sub> < 90% uden O <sub>2</sub> RF > 30	SpO <sub>2</sub> < 95% uden O <sub>2</sub> RF > 25	SpO <sub>2</sub> ≥ 95% uden O <sub>2</sub> RF 8-25			
Puls > 140 BT <sub>max</sub> < 80 mmHg	Puls > 120 eller < 40 BT <sub>max</sub> < 90 mmHg	Puls > 110 eller < 50	Puls 50-110 BT <sub>max</sub> ≥ 90 mmHg			
GCS ≤ 8	GCS: 9-13	GCS = 14	GCS = 15			
Tp < 32° C	Tp > 40° C Tp 32-34° C	Tp > 38° C Tp < 35° C	Tp 35-38° C			
For patienter med kendt KOL nedsættes saturations-grænsen med 5%						
SpO <sub>2</sub> < 85% med O <sub>2</sub> SpO <sub>2</sub> < 75% uden O <sub>2</sub>	SpO <sub>2</sub> < 90% med O <sub>2</sub> SpO <sub>2</sub> < 85% uden O <sub>2</sub>	SpO <sub>2</sub> < 90% uden O <sub>2</sub>	SpO <sub>2</sub> ≥ 90% uden O <sub>2</sub>			
Kontaktårsagskort/Triagekriterier:		Samlet Triage-niveau:				
		<div style="display: flex; justify-content: space-around;"> <div style="width: 15px; height: 15px; background-color: red;"></div> <div style="width: 15px; height: 15px; background-color: orange;"></div> <div style="width: 15px; height: 15px; background-color: yellow;"></div> <div style="width: 15px; height: 15px; background-color: green;"></div> <div style="width: 15px; height: 15px; background-color: blue;"></div> </div>		TRAUMEKALD	SKADEKALD 1	SKADEKALD 2
Smerter i hvile? <input type="checkbox"/> Nej <input type="checkbox"/> Ja, beskriv:		VAS / 😊 / FLACC 0 1 2 3 4 5 6 7 8 9 10				

Figure 4.6: *Triage type assessment form.*

The level of severity of the patient's health is proportional to his/her priority in the treatment queue.

*Red-type* patients are in an immediately life-threatening condition (e.g critical injury, cardiac arrest etc) and have to be treated immediately.

*Orange-type* ones are in an imminently life-threatening condition (e.g serious chest pains, breathing difficulty etc) and have to be treated within 15 min.

*Yellow-type* patients are in a potentially life-threatening condition (e.g severe illness, major fractures etc) and have to be treated within 60 min.

*Green-type* ones are in potentially serious condition (e.g foreign body in the eye, sprained ankle, migraine) and have to be treated within 180 min.

As for the *Blue-type* patients, these are in a less urgent condition, (e.g rashes or minor aches and pains) and have to be treated within 240 min [14].

Some of these patients are forwarded to the Wards while others occupy a bed inside the ED department. In the present assignment, the beds within the ED department will be named as the 48hr bed department, since each patient can occupy a bed in the ED for maximum 48hrs.

## 4.3 Input Data

In the present section all the Input data which were provided from the hospital and will be used in the simulation are presented; some of them are predictions of the performance of the future hospital based on the current's one.

### 4.3.1 Arrival Rate

The number of patients arriving at the hospital per hour (both by ambulance or on their own) was given for each hour of a whole year, based on the gathered data from 01/08/2011 to 30/07/2011. The total number of incoming patients at the ED was 45355. From the analysis of the data, the busiest months were proved to be March, December and January, as it can also be seen in *Figure 4.7*.

Moreover, the average number of arrivals per hour for the most and least busy weeks can be seen in *Figure 4.8*. It can be noted that the hours between 10.00 to 15.00 are the busiest ones.

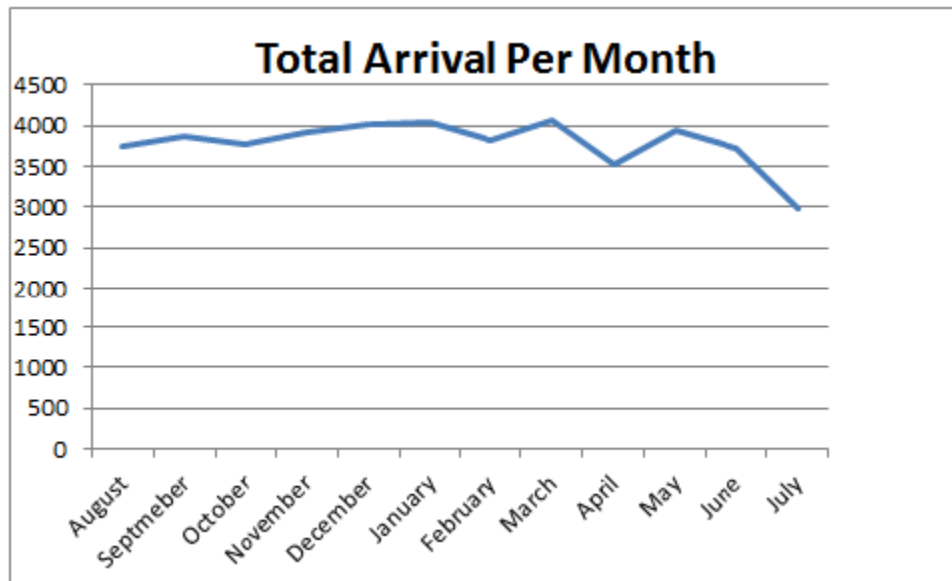


Figure 4.7: *Total number of incoming patients per month.*

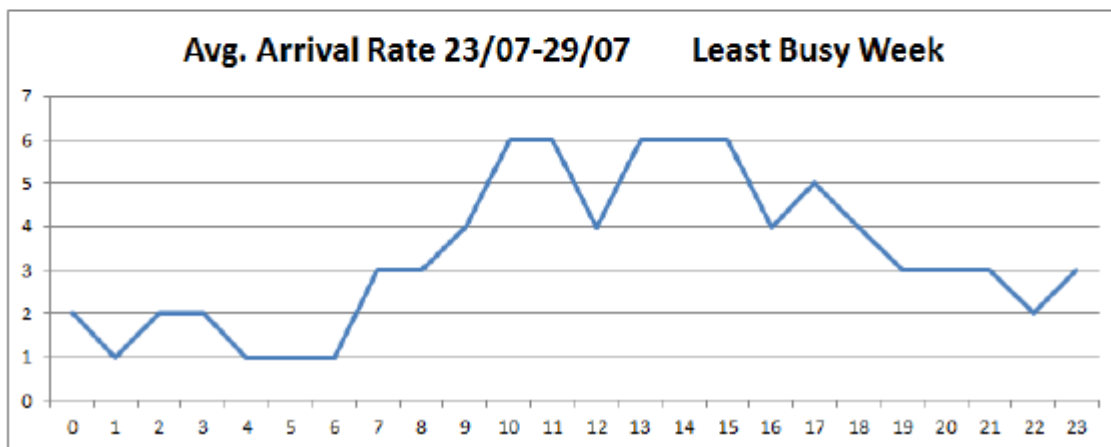
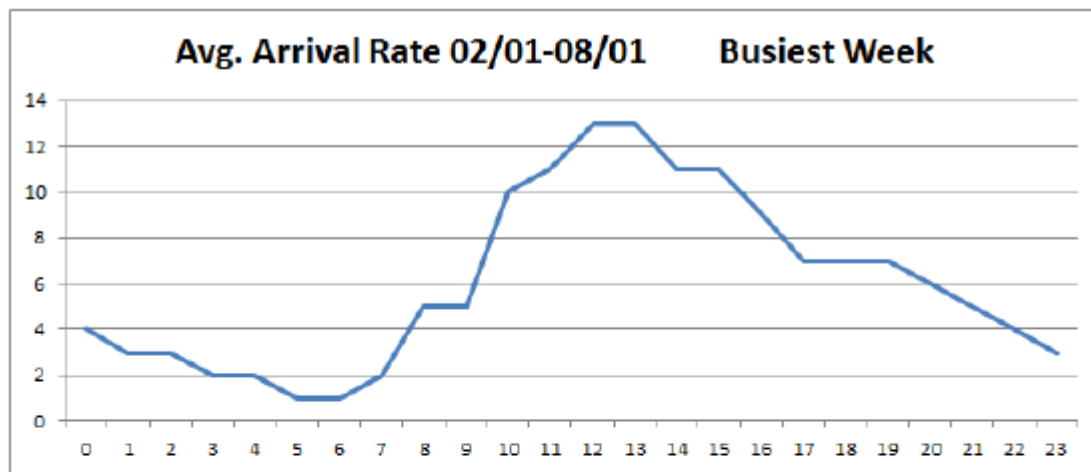


Figure 4.8: *Average number of incoming patients per hour for the most and least busy weeks.*

### 4.3.2 Patient Types

The distribution of patients across the triage types is presented in *Figure 4.9*. Moreover, the patients are divided into 12 pathology groups according to the type of their health problem (e.g geriatric, dermatological etc.) as it can be seen in *Table 4.1*, where the probability of a patient being a specific type along with the probability of the patient of that type going to the ED or straight to the Wards is also given. Additionally, the average time (along with the respective st.dev) that an ED patient occupies a 48hr bed is also provided. However, no relevant information regarding the distribution of the pathology groups into the different triage types is given.

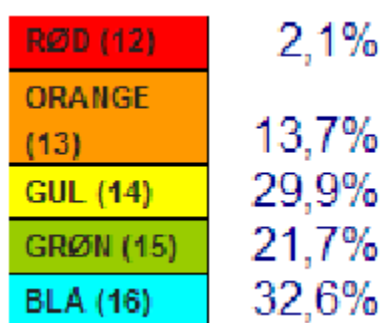


Figure 4.9: *Triage types distribution.*

Group Type	%	% ED	Avg. hours	+/-	% Wards
DS Total	1,02	0,00	0,00	0,00	100,00
G Total	2,23	22,85	9,16	1,00	77,15
H Total	1,54	100,00	9,83	1,00	0,00
I Total	19,98	98,02	12,36	1,00	1,98
K Total	14,95	100,00	11,53	1,00	0,00
L Total	18,92	96,13	12,11	1,00	3,87
M Total	7,85	95,95	10,81	1,00	4,05
N Total	8,59	22,82	21,33	3,00	77,18
U Total	3,51	100,00	11,53	1,00	0,00
Y Total	20,02	55,28	13,40	2,00	44,72
P Total	0,15	0,00			100,00
Z Total	1,24	0,00			100,00
<i>Total</i>	<i>100,00</i>	<i>78,85</i>			<i>21,15</i>

Table 4.1: Patients' Pathology Groups.



### 4.3.3 Statistical Analysis on the data

First of all, the input data were checked and cleaned, adding some hours that had not been recorded during the year in order to have 24hrs in every simulated day, something that is crucial for the reliability of the future decisions (e.g estimating the number of nurses in each shift). Then, the assumed arrival rate at these added hours was set to 0, since there was no other available information and also because the missing hours were usually night ones, when it is very likely to have an arrival rate of 0.

Although it is unknown how the data were gathered, an attempt to understand their behavior was made by applying statistical analysis. With the use of Arena's Input Analyzer, initially a general arrival hourly rate was attempted to be generated. However, using arrivals of all the hours as an input, none of the known distributions could fit the general hourly arrival rate with a confidence interval of  $\alpha = 0.05$ , and therefore all of the resulting p-values from the chi-square test were  $p < 0.05$ .

Therefore the arrival rates were sorted for each of the different 24 hours and the distributions that could best fit the arrival rate of each hour were generated. It can be seen from *Table 4.2*, that near the morning and the evening shift Normal-like distributions, (Weibbul, Beta), were fitting better the arrival rates. Since it is very common to have Poisson distribution for arrival-related processes, some Poisson distributions appeared as first or second candidates for fit, fewer though than expected. However, as it is unknown how exactly the data were collected it is unsafe to draw any conclusion from the above.

Due to the fact that it is impractical and not logical to use different arrival distributions for each hour, after several trials the hours were grouped such as an arrival distribution could fit each group with a decent p-value (chi-square test), as it is similarly done in Swartzman's article [17]. The formulated time-groups and the resulting distributions can be seen in *Table 4.2*.

Hour	Suggested Distribution	p-value	Suggested Distribution
0	Poisson	0.717	
1	Beta	0.3	POIS(2.51)
2	Poisson	>0.75	p=0.181
3	Gamma	>0.75	
4	Weibull	0.647	
5	Weibull	0.645	-0.5+ GAMM(0.931,2.36)
6	Erlang	0.346	p=0.553
7	Weibull	0.636	
8	Beta	$\geq 0.75$	
9	Beta	0.103	
10	Normal	0.432	-0.5+24*BETA(1.75,3.12)
11	Beta	0.241	p=0.154
12	Beta	0.496	
13	Beta	0.018	
14	Normal	0.587	
15	Weibull	>0.75	
16	Weibull	>0.75	-0.5+GAMM(1.74,4.56)
17	Weibull	0.153	p>0.75
18	Weibull	>0.75	
19	Gamma	$\geq 0.75$	POIS(5.04)
20	Poisson	>0.75	p>0.75
21	Beta	<0.005	
22	Beta	0.234	POIS(4.07)
23	Weibull	0.197	p=0.251

Table 4.2: *Results of the statistical analysis on the arrival data.*

It can be noticed that from evening till morning, the arrival rates fit closer to a Poisson distribution whereas during the morning they fit better to a Gamma and Beta.

These statistically approximated arrival rates for the grouped hours were tested in the model. However, by doing so, the number of input patients (entities created) proved to be much less than the 45355 patients which were expected annually. Therefore, it was concluded that this number of created entities is not a sufficiently accurate representation of the model and that the initially given annual arrival data for each hour of the year should be used for the following tests.

It can be noted here that the statistical arrival rates are particularly useful for validating the model's robustness in case of changes, or for creating a more generic model or even when some of the input data are missing or are not reliable. Moreover, approximating the arrival rate with a statistical distribution, could be especially useful when the size

of the given input sample is not as large as the one presented in this study (one year).

For the present case, it would have been better if the arrival data were gathered in smaller time intervals (e.g 5 min) or even in real time (e.g by taking the information straight from the triage nurses' filled forms). By doing so, the simulated model would have been closer to reality and more accurate statistics and suggestions would have been made. Moreover, for the creation of a general arrival rate, the division between weekdays and weekends would have been more accurate since the arrival behavior differs considerably between these days.



# Chapter 5

## The Arena Model

In the current chapter the Arena model is presented, along with the made assumptions and the activity diagram.

In the second part the final Arrival Rate is chosen and the final goals of the project are discussed and analyzed: the estimation of the number of *Triage Nurses* and the needed *48hr Beds*.

### 5.1 Model

The boundaries of the created simulation model are the ED's entrance and its exit. Only the entrance of the Wards department is taken into account since it is sometimes related with the ED department (e.g night shift).

#### 5.1.1 Assumptions

- The transportation time through the whole system is not considered since the present simulation refers to the future hospital and the exact layout plans are not known.
- The only considered resources in the ED are the reception nurse, the triage nurses and the 48hr beds. No relevant data were given regarding other resources (e.g number of needed doctors for each type of examination and relevant process times).
- If a red-type patient enters the system then he is forwarded straight to the Wards, without even entering the reception and the triage process.

- In the present model every patient that stays in the ED and is not forwarded to the Wards, occupies a bed in the 48hr department. That might seem illogical, especially for the blue-type patients, who comprise the bigger percentage of patients and are usually treated without needing to occupy a bed. But, the given input data is extracted after removing the patients that do not occupy a bed.
- The probabilities of a patient being a specific triage type and belonging to a certain pathology group are considered independent as there is no given correlation between these attributes. For example, the probability of a patient being pathology type G is the same for all the triage types. That also makes the time that each patient spends in the 48hr beds independent of his triage type, meaning that a G patient spends  $9.16 \pm 1$  hrs in a 48hr bed, regardless if he is red, orange, blue type etc.
- The process time at the reception is assumed to follow a Normal distribution of (1,0.5) min. Moreover, the time that a nurse needs to assess the type of patient in the triage process is also assumed to follow a normal distribution. However, it is considered that some types are more easily recognizable than others (e.g blue type patients) and therefore the mean assessment time and the respective st.dev differ for each type of triage patients.
- It is assumed that the patients are assessed in the triage process with the FIFO rule and they have no priority depending on their condition. However, every patient should be assessed from a triage nurse within 10 min.
- It is considered that a patient has priority in being assigned a 48hr bed depending on his triage type. Additionally, it is assumed that all the patients can be visited by a doctor if they are assigned a bed. Therefore, for each triage type of patient there is a time limit within which he has to be seen by a doctor (e.g 15 min for an orange-type patient) which is equal to the time limit within which he has to have a bed.
- The desired utilization of the 48hr beds is 66% such as that the ED will still be able to perform in a potential increase of the incoming patients, maintenance, or in any other alteration of the current stage.
- In reality, when a patient leaves the 48hr department a bed becomes practically available. However, the bed according to the IT system is still not available for

some time; this time is not considered in the present simulation and the bed becomes instantaneously available when a patient leaves.

- A patient can exit the 48hr beds and leave the hospital any time.
- For internal planning reasons, all the Wards are closed for new patients at night (8 p.m-8 a.m). Therefore, it is assumed that the patients that had to go to the wards at night can stay in the ED instead, and occupy a bed there. If they are treated inside the ED before the wards open, then they exit the hospital. Otherwise, they are forwarded to the wards when these open. Since no relevant data was available, their treatment type depends on their pathology group and is assumed to be equal to the one that an ED patient of that group spends on the 48hr bed (see *Table 4.9*). So the time that each ward patient spends on the ED at night is the minimum between his treatment time and the time until the wards open.
- As for those patients that have to be forwarded to the Wards after being treated in the 48hr beds, if it is night then they continue to stay in their 48hr bed, until the wards open.

### 5.1.2 Activity Diagram

An activity diagram, representing the process flow of the created simulation model can be seen in *Figure 5.1*.

# BISPEBJERG HOSPITAL

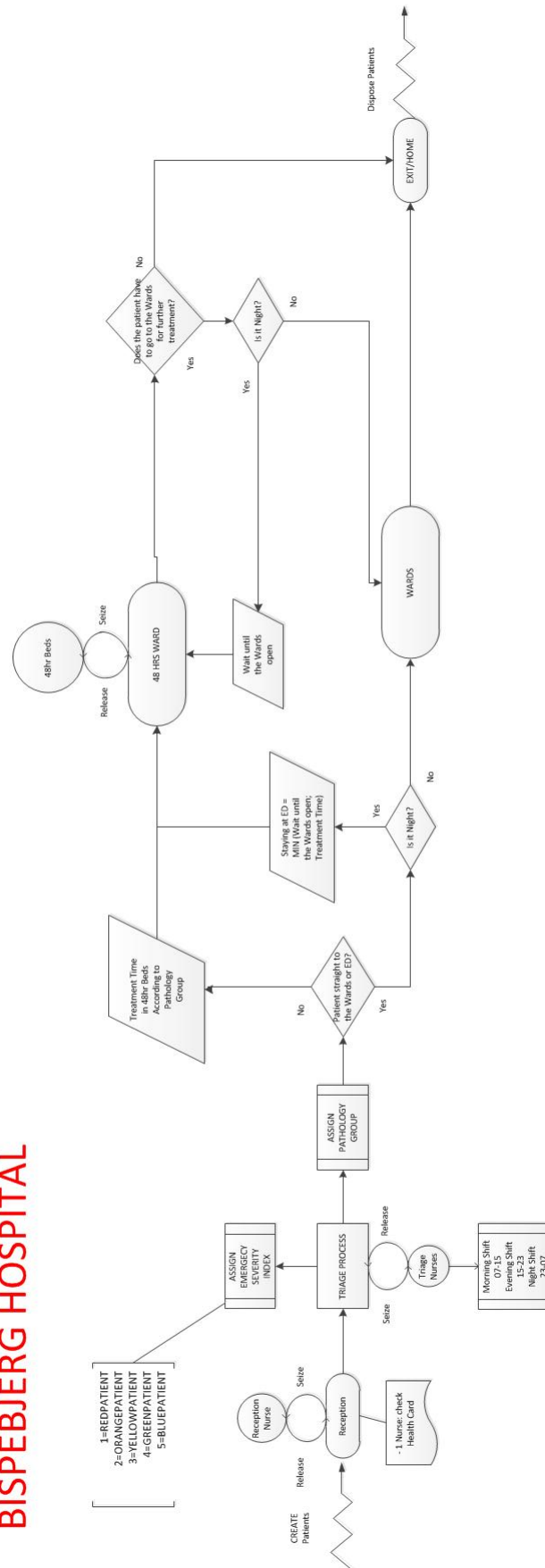


Figure 5.1: Activity Diagram.



### 5.1.3 Arena Model

In the current section, the whole Arena Model is presented and explained. The final Arena Model is presented in *Figure 5.2*.

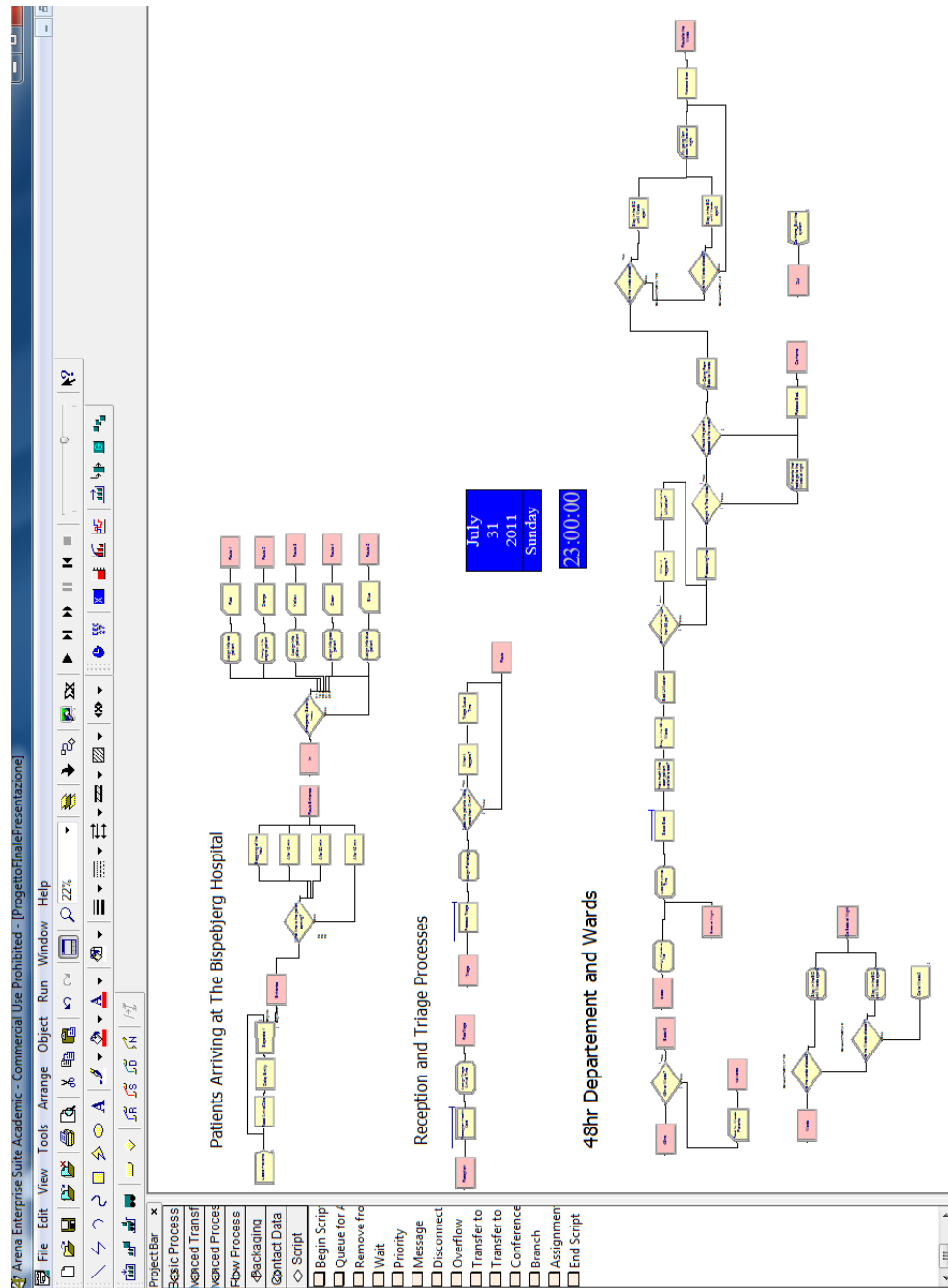


Figure 5.2: *Arena Model.*

In order to facilitate the explanation of the model, it has been divided in three parts: *Patients Arriving at The Bispebjerg Hospital, Reception and Triage Processes, 48Hr Department and Wards*; a single paragraph is dedicated to each of the parts discussed above.

## **Patients Arriving at The Bispebjerg Hospital**

*Figure 5.3* represents the first step of the model.

For each hour of the whole year the model reads the number of the incoming patients, line by line from the given excel file and then the patients are released to the system (different ways of patients' release are presented and discussed in *section 4*).

The moment a patient (entity) enters the system, he is assigned a number of attributes that will influence his flow through the system and the processes he will be involved in. Firstly his triage type (entity type) is randomly decided, according to the given probabilities of a patient being red-type, orange-type etc. His triage type for simulations reasons that will be explained later, is not symbolized by color but rather by the respective emergency severity index, meaning red-type is Type 1 patient for the simulation, orange-type is Type 2 etc. ("*myTriageType*").

Although he has not proceed to the triage yet, (where his triage type will be formally given), he is assigned his triage type earlier for simulation reasons, since the red-type patients will be forwarded straight to the Wards and not proceed through the triage process. Moreover, according to his assigned triage type, the time he will spend in the triage assessment process ("*myTriageProcTime*") is also given. Additionally, the patient is also assigned the time he spends in the reception ("*myReceptionTime*") although this is considered to be the same for all the types of patients. After all the attributes are assigned to the patient, he proceeds to section 2.

## Patients Arriving at The Bispebjerg Hospital

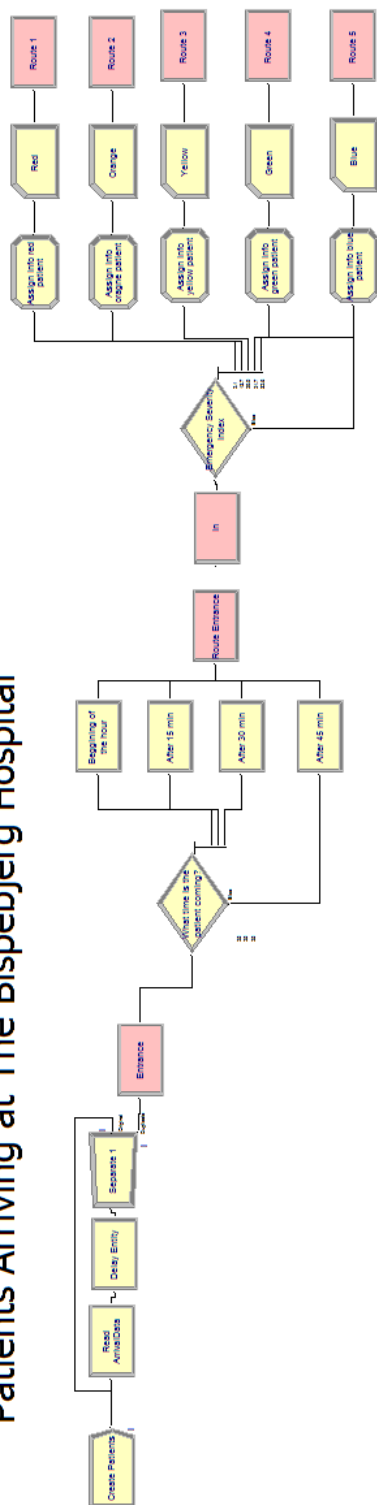


Figure 5.3: *Patients Arriving at The Bispebjerg Hospital*

## Reception and Triage Processes

When the patient arrives to the reception, he spends there time equal to "*myReceptionTime*". In that process, one reception nurse is occupied as a resource.

After the reception, the patient is forwarded to the triage process, where a number of triage nurses is scheduled. For each patient, the time it takes the triage nurse to assess the patient's triage type is, as mentioned earlier, "*myTriageProcTime*". Furthermore, the waiting time of each patient at the Triage process is recorded, where how often and how much a patient exceeds the 10 minutes waiting time limit is analysed.

Afterwards, the patient is assigned his pathology category, according to the given probabilities of a patient belonging to category G, K etc., as seen in *Table 4.1*. Then, depending on his assigned pathology category several other attributes are attached further to the patient ; "*myPerc.48hrs*", "*my48Time*" and "*myGoToWard*". "*myPerc.48hrs*" is the probability that the patient has to go straight to the Wards or else he has to continue his flow through the ED. Then, "*my48Time*" is the time that a patient will occupy a bed in the 48hr department, if he will not go to the Wards. Finally, there is a probability ("*myGoToWard*") that after a patient has finished his treatment in the 48hr beds he will have to continue to the Wards for further examinations.

These processes can be seen in *Figure 5.4*.

## Reception and Triage Processes

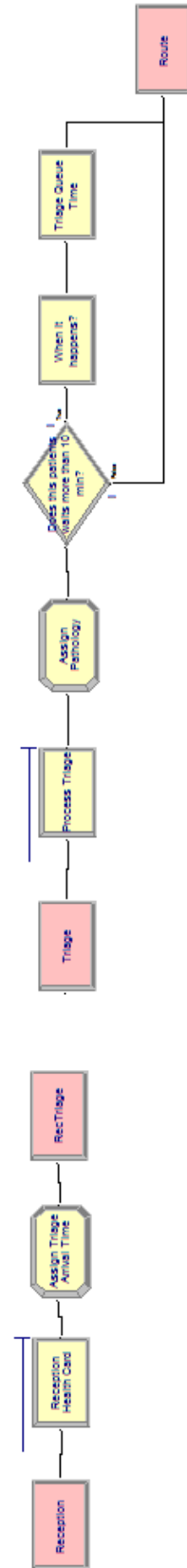


Figure 5.4: *Reception and Triage Processes.*

## 48hr beds and Wards

The 48hr beds and Ward sections of the Arena Model are depicted in *Figure 5.6* and *Figure 5.7*.

Then the patients are forwarded and as said before, "*myPerc.48hrs*" decides if they should go to the ED beds or to the Wards. ED patients are assigned the "*myStraighTO-Wards*" value to 0, whereas for the Ward patients that value is 1. By doing so, the system keeps track of what type of patients they are. So, in the night, when the Ward patients become ED ones, they still keep their Ward identity. Because, when they are in the ED there is, as stated before, the probability ("*myGoToWard*") of continuing to the Wards after being treated in the ED. However, that probability does not apply for the patients that have already came from the Wards, because if it did these patients will have being doing a circle from the Wards to the ED and then to Wards again.

When a patient has to be assigned a 48hr bed, he is prioritized according to his triage type. For example, an orange patient has ("*myTriageType*") of 2 and he has a priority of being assigned a bed over a yellow-type patient who has a ("*myTriageType*") of 3.

For the ED patients, after a bed is available, the patient occupies it for a time defined by his "*my48Time*" attribute. Then, it is checked if the patient is indeed an ED one, and if he also has to be forwarded to the Wards. If not, he can exit the system and his bed is released. Similarly, if it is morning and he has to go to the Wards, he also releases the bed and exits the system. If it is night though (8 p.m - 8 a.m) when Wards are closed, then he continues to occupy his ED bed until the Wards become open again, and so he will exit the system.

As for the patients that had to go straight to the Wards after the triage, they are forwarded to the Wards and thus exit the ED system instantly. However, in the night when the Wards are closed they are forwarded to the ED and they are assigned a bed there. The time they are staying in the 48hr beds is defined by "*my48Time*" which in that case is calculated by  $MIN("my48Time", Time\ until\ the\ Wards\ open\ again)$ . So, assuming that the patient's treatment time is the time defined by his pathology type, (the one used for ED patients), the Ward patient can stay in the ED until his treatment finishes or until the Wards open again where he will continue being treated.

During the simulation, statistics are gathered regarding the 48hr beds utilization and

also how often and how much that exceeds the desired limit of 66%. Additionally, the waiting time in every process for all the triage type of patients is tracked and recorded.

Moreover, the simulated system is animated as seen in *Figure 5.5*. Since no layout plans were known, the designed ED is rather simple. The clock and calendar represent the current simulation time. Also, when a patient occupies a bed, then he can be seen in that bed as long as he occupies it, until he releases it and the bed becomes empty again.

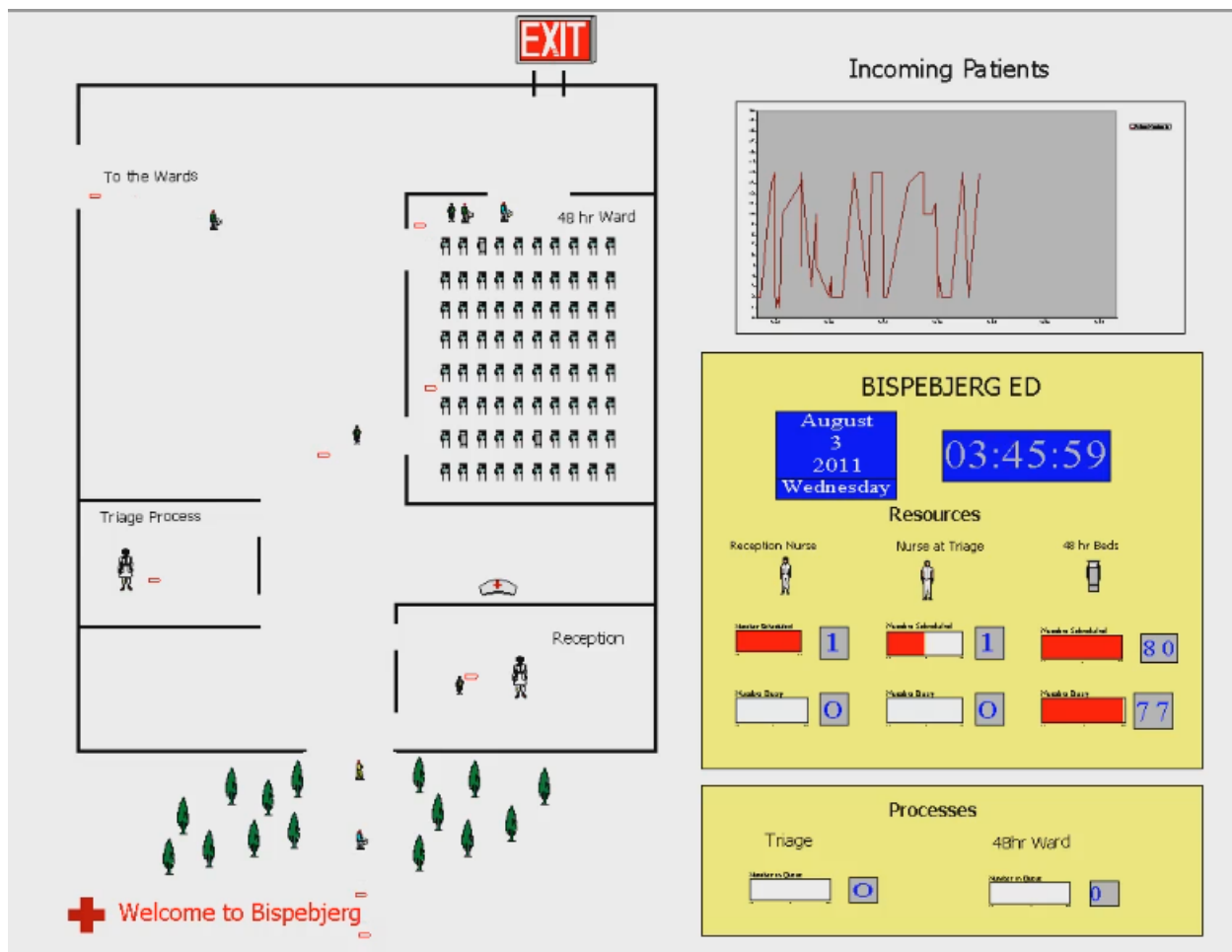


Figure 5.5: *Arena Model - Animation.*

Finally, an index of all the used attributes in the system (which usually represent the patients' characteristics), can be seen in *Table 5.1*.

Entity Types	Description	Value
<i>Red Patient</i> <i>Orange Patient</i> <i>Yellow Patient</i> <i>Green Patient</i> <i>Blue Patient</i>	Patient's Triage Type	1 2 3 4 5
Patient's Attributes	Description	Value
<i>myWard</i> <i>myPerc.48hrs</i> <i>my48Time</i>	Patient's Pathology Group Probability to go the 48hrs Ward Proccesing Time at the 48hrs Ward	e.g. G,H,K,L [DISC(0.145,1,0.379,2,0.651,3,...) e.g. 0.228 depending on Pathology Group e.g. NORM(9,1) hrs depending on Pathology Group
<i>myTriageProcTime</i>	Processing Time at the Triage	Triage Type1 = 0 min Triage Type2 = NORM(5,3)min Triage Type3 = NORM(7,3) min Triage Type4 = NORM(4,3) min Triage Type5 = NORM(2,3) min
<i>myTriageType</i> <i>myReceptionTime</i> <i>myStriaghtTo Wards</i> <i>myGoTo Ward</i>	Patient's Triage Type Processing Time at the Reception Does a patient go to the wards after the 48hrs ward? Does a patient go straight to the ward?	1,2,3,4,5 NORM(1,0.5) min 0=No, 1=Yes e.g. 0.367 depending on Pathology Group
<i>myArrival</i> <i>myArrivalTriage</i> <i>myArrivalTime48</i>	Attributes needed for the extrapolation of additional KPIs	TNOW=called to record the current time

Table 5.1: List of Entity Types and Attributes for each patient of the system.



# 48hr Departement and Wards

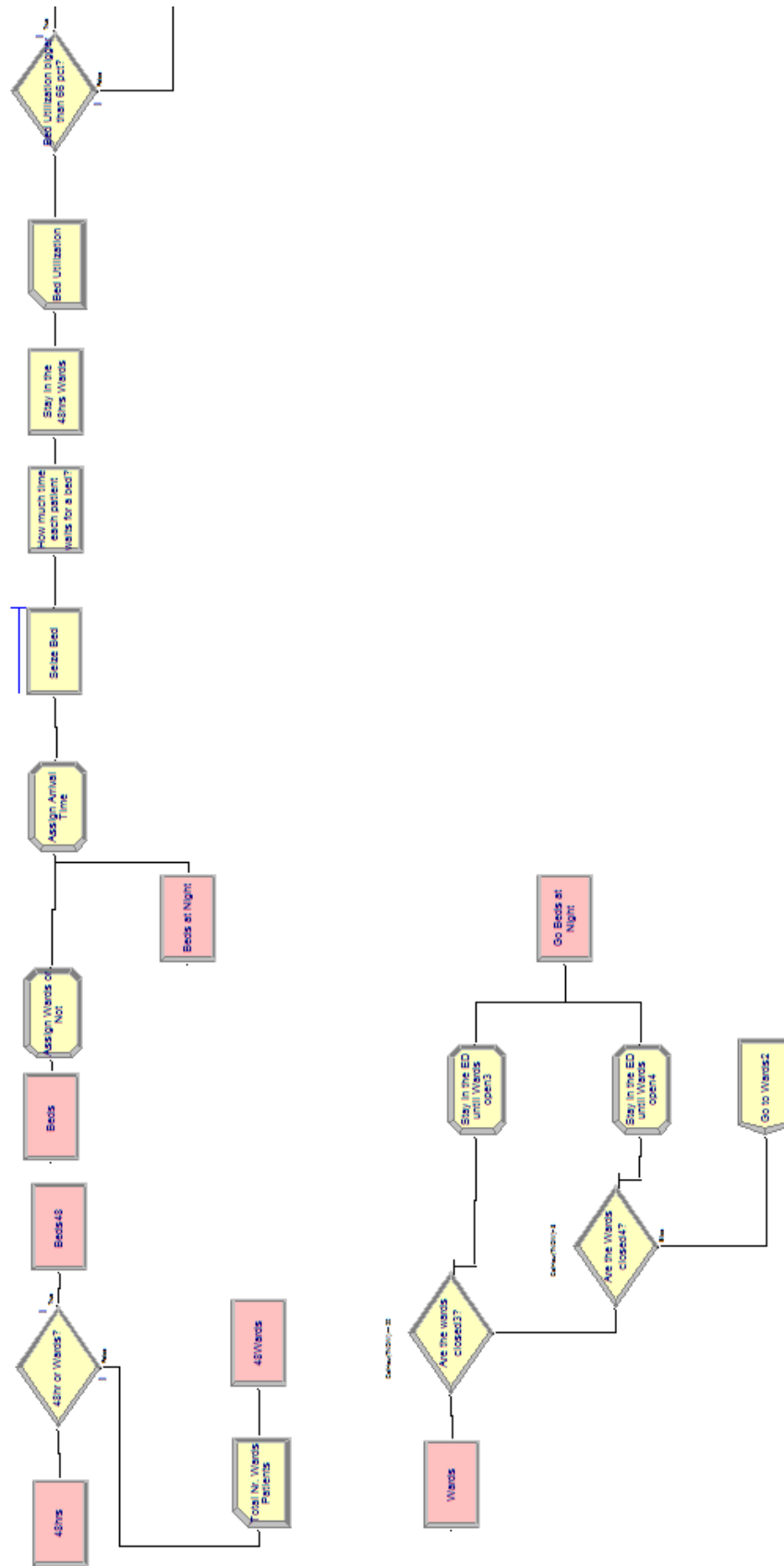
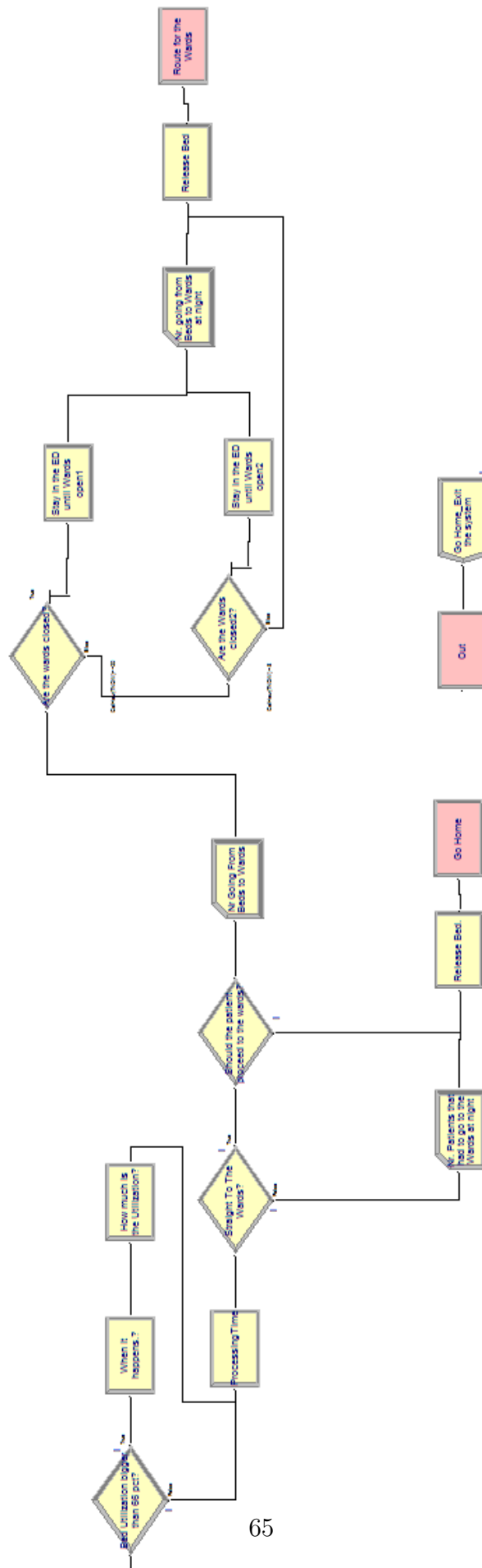


Figure 5.6: Arena Model - 48hr Department and Wards, Part 1.



## Run Setup Configuration

For all of the following tests, the model was decided to run for 4 replications, meaning for four years, such as the resulting statistics will have a satisfying half width. The desired accuracy was a compromise between all the half widths of the tracked KPIs. However, a formula to calculate the needed number of replications such as a desired half width will be obtained for a specific KPI can be found in Rossetti's book [18].

When multiple replications are executed in *Arena*, *Arena* will automatically compute a 95% confidence interval for your performance measures. *Arena* doesn't report the standard deviation, but instead directly reports the half-width value for a confidence interval. Making a pilot run of  $n_0$  replications, the reported half-width can be used to determine how many replications are needed to be close to a desired half-width bound. This method is called the half-width ratio method. Let  $h_0$  be the initial value for the half-width from the pilot run of  $n_0$  replications; after few simplifications, the formula can be expressed as follows:

$$n = n_0 * h_0^2 / h^2$$

Since in the present project there is not just one parameter which has to be analyzed, it is hard and probably useless to iterate the formula for each of the needed KPIs; therefore, it has been decided to increase the number of replications until the half-width reached a reasonable value (which was thought to be less than 5% of the selected parameter). It can be seen in *Figure 5.8* as an example that, after 4 replications, the goal has been achieved; having on the number of incoming patients half-widths of around the 2% of the value.

In addition, the model runs continuously, meaning that the start of the next replication continues from the last stage of the previous one. So, if in the end of the first year some patients are still in the system (occupying beds for example), these patients keep being in the system in the start of the next year. In that way, the model becomes more realistic and is already in a form of a steady state at the start of the next replication.

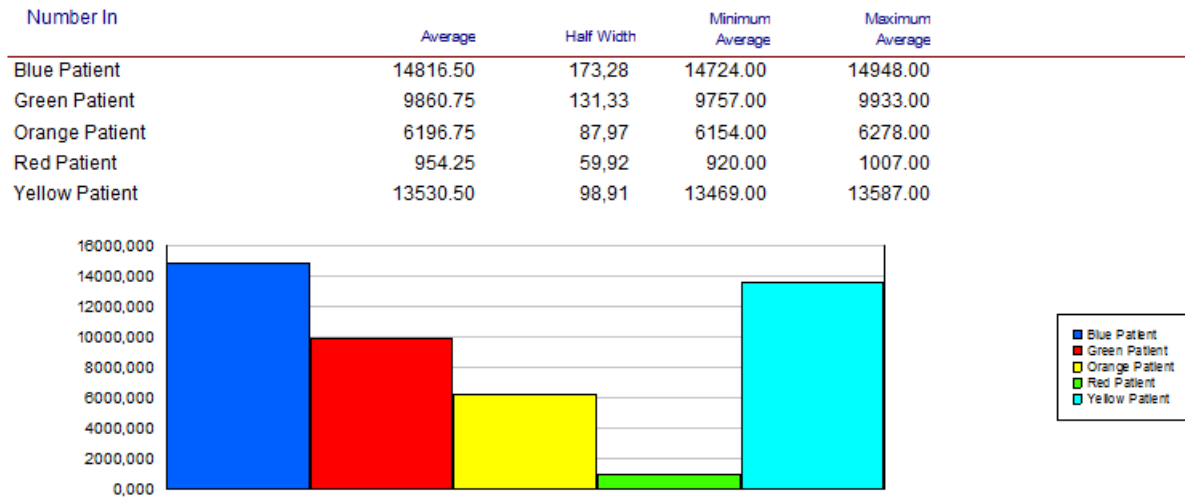


Figure 5.8: *Checking the number of replications.*

#### 5.1.4 Model Validation

An important step during the build-up of a simulation model is its validation.

As described in 2.3, the goal of the validation is to determine if the model adequately represents the real system. In order to perform this kind of analysis different data given from the Bispebjerg Hospital have been compared with the output of the current model.

As can be seen in *Table 5.9*, output data were collected about the twelve different department where patients can be sent after the Emergency Department. In the first column the data given from Hospital are shown meanwhile, the second one represents the results obtained from the simulation model. It must be noticed that the results given by the Arena Model can't be precisely the same of the reality; this can be explained within two reasons:

1. The model was run for 4 replication (as explained in 5.1.3 ); therefore, the results shown in *Table 5.9* are obtained as an average of the results of each replication.
2. A simulation software is just a tool to recreate the reality and it's made by assumptions and statistic. It's stated in the definition of simulation itself that the reality is modeled assuming a certain error. The statistic nature of a simulation software explains that nothing can be perfectly recreate without an even small standard deviation.

As can be seen in the last column the error is calculated (only considering the mean of the model's output for ease of use): each error is between 1 and 6 %, value that has been considered adequate for this current model.

WARDS	INPUT	OUTPUT	% ERROR
Z	568	552±4.5	2.8 %
DS	467	438.5±21.83	6.1 %
G	1024	1008±26.05	1.6 %
H	709	679.25±68.52	4.2 %
I	9178	8926.5±47.38	2.7 %
K	6866	6647.75±112.69	3.2 %
Y	9196	8894.50±190.75	3.3 %
L	8688	8367.75±22.59	3.7 %
M	3605	3433.50±112.02	4.8 %
N	3944	3843±49.35	2.6 %
P	68	67.75±6.8	3.7 %
U	1614	1546±71.61	4.2 %

Figure 5.9: *Comparing the Outputs.*

As far as the model's validation is concerned, another tool can be really helpful to analyze if the model is working properly : the creation of the 2D/3D animation (picture shown in *Figure5.5*).

During the run of the model, with the animation on the side it can be possible to control if Arena reads in the right way all the information given by the programmer.

E.g. : thanks to the 2D animation it was possible to detect and fix an error about the way Arena reads the shifts of the nurses in the Triage Process.

The model validation consists also in the inspection of the Assumptions made before: the most relevant ones are discussed in *Section6.2*, where different scenarios are discussed and analyze.

## 5.2 Deciding the Arrival Rate

The given arrival rate refers to the number of patients arriving to the hospital in an hourly basis. When the model reads the excel file without further processing, then all the patients that are about to arrive during an hour are released to the system instantaneously in the beginning of that hour. In that way, the system becomes more congested than reality where the patients' arrival is distributed randomly during the hour and not in the beginning of it.

In order to create a model closer to reality and thus proceed to more accurate conclusions on a later stage, additionally to the 1hr one, different arrival rates were created and compared, to decide which one will be used on the test model.

### *30min Arrival Rate*

The model still reads line by line from the excel, meaning hour by hour. However, if for example there are  $y$  patients arriving in an hour, then there is 50% probability that  $y/2$  patients will arrive at the beginning of the hour and another 50% that  $y/2$  patients will arrive after 30 min from the start of the hour. In that way, patients arrive to the model every half an hour.

### *15min Arrival Rate*

The procedure is similar to the 30min Arrival one. However, if  $y$  patients should arrive in an hour, then there is 25% probability that:  $y/4$  patients arriving at the start of the hour,  $y/4$  after a quarter,  $y/4$  after half an hour and other  $y/4$  after 45 min.

No arrival rates with smaller intervals were tested because the test model, on which the suggestion of the needed resources will be based, should still be slightly congested such as the suggested resources will still perform well under a potential slight congestion.

Using Arena's process analyzer some of the model's KPIs were compared for different arrival rates. The number of triage nurses in the 3 shifts was fixed for all the runs to 2-2-2, while the number of 48hr beds was fixed to 75. The results can be seen in *Table 5.2*.

Scenario Properties			Responses		
Arrival	NReps	Triage Wait- ing Time	48hrs Wait- ing Time	48hrs Beds Avg. Utilization	Patients Number Out
1hr	4	3.937	28.282	0.711	45355
30min	4	1.678	23.409	0.711	45359
15min	4	0.727	23.520	0.712	45359

Table 5.2: Comparison of resulting KPIs for different Arrival Rates.

It can be seen that with the same number of replications (NReps), beds and nurses, the 1hr model is the most congested one. The more often the patients are distributed to the system, the less congested the system becomes and the waiting time at the triage along with the waiting time at the 48hr beds decreases. So, with the same number of resources the process becomes more efficient and the number of patients exiting the system increases.

Therefore, it was decided except from the initial 1hr arrival model (which uses the given hourly data without any modifications) to use also the 15min arrival one, since it will provide a more logical evaluation of the needed number of resources. Moreover, by deciding using both of these arrival rates in the next section, an upper and a lower bound of the number of needed triage nurses will be obtained, based respectively on a more congested model and on a less congested one.

### 5.3 Estimating the Number of Triage Nurses and Determining the final Arrival Model

In the present section the needed number of nurses for each shift will be estimated for the 1hr and the 15 min arrival rate. The hospital shifts are : *Morning Shift* (7 a.m - 3 p.m), *Evening Shift* ( 3 p.m - 11 p.m) and *Night Shift* (11 p.m - 7 a.m).

Using Arena's OptQuest and a feasible range of nurses between 1 to 3, different trials were made such as the following model will be optimized:

$$\text{Minimize : } Nr. \text{ of Nurses} + \text{Avg. Waiting time at the Triage} \quad (5.1)$$

$$s.t \text{ Avg. Waiting at Triage} < 10 \text{ min} \quad (5.2)$$

So the objective (1), is not only to minimize the Avg.Waiting time at the Triage process but also to minimize the number of needed nurses, since if that second part was not included at the objective then the model would suggest the maximum number of given nurses to be used because this would result in the minimum Triage waiting time. Therefore, the current optimization is a multi-objective one as, except for a small waiting time at the Triage, an also logical number of the allocated resources is attempted to be achieved. The objective would have been more accurate if instead of the minimization of the number of nurses the minimization of the cost of the used nurses would be used, since the night-shift nurse probably costs more to the hospital than the morning and evening one. However, no information was given regarding the payment of the nurses for the different working hours and so the use of the number of nurses in the objective was considered a logical alternative. Moreover, constraint (2) secures that, in average, patients should not wait more 10 min to be assessed in the triage process.



### 5.3.1 1hr Arrival Rate

Using the hourly Arrival Rate, the model presented above was optimized. The algorithm was iteratively trying different combinations of nurses within the given range, disregarding the ones that resulted in infeasible solutions (Avg.Waiting time < 10 min.). In each iteration, the best solution (minimum objective) found so far was saved. These algorithm steps over local optimas are presented in *Figure 5.10*.

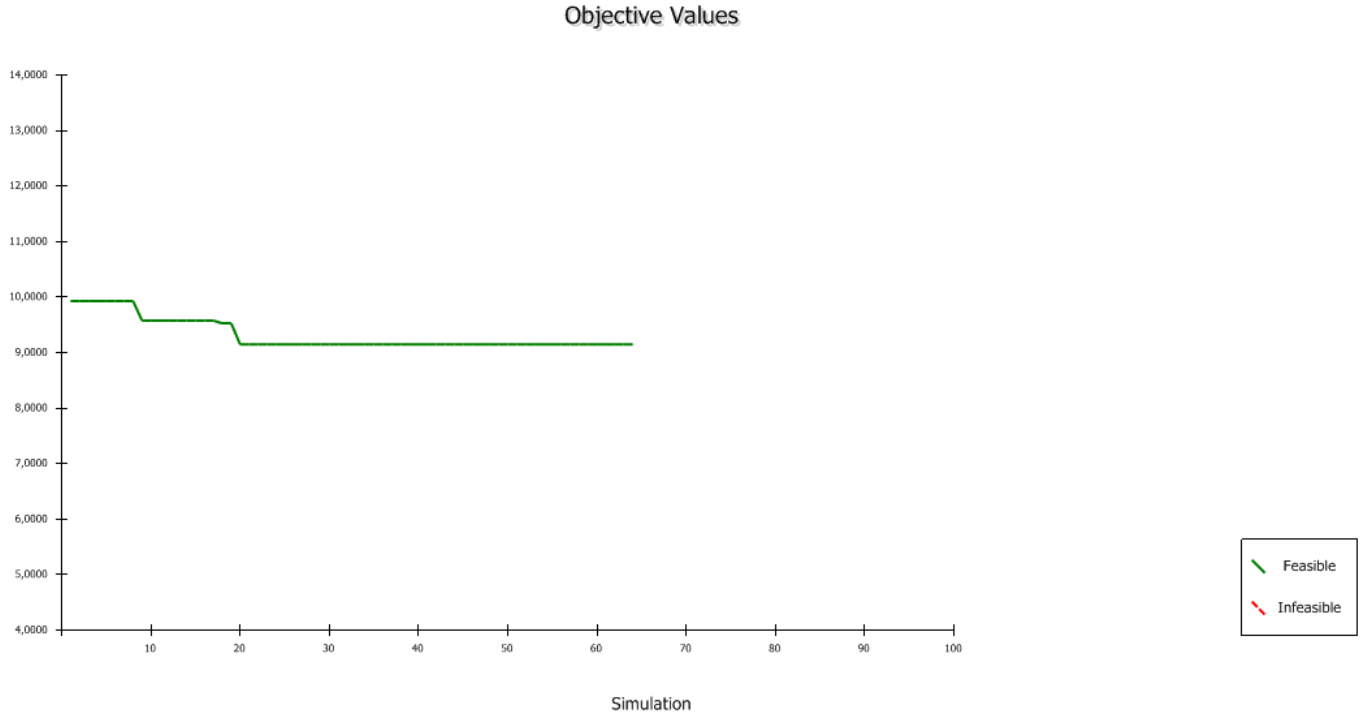


Figure 5.10: *1hr Arrival - Best solutions found through the different iterations.*

However, the minimization of the average waiting time cannot be considered as the sole criterion for making reliable decisions. Therefore, the optimal solution, (3-3-1 nurse allocation at the shifts), which resulted to the minimum objective along with different good solutions, were also tested further in regards to how often and how much in average a patient has to wait more than 10 min in the Triage queue, meaning how often the resulting nurse allocation may prove to be insufficient. The results can be seen in *Table 5.3*.

Shifts	Nr.Nurses	Avg.Wait.Time	Avg.Max (>10 )	Max	Wait.Time>10
Morning Shift	3	2.15±0.03	14.75	62.79	6%
Evening Shift	3				
Night Shift	1				
Morning Shift	3	3.21±0.03	14.89	63.64	10.7%
Evening Shift	2				
Night Shift	1				
Morning Shift	2	4.6±0.03	15.47	57.29	17.9%
Evening Shift	2				
Night Shift	1				
Morning Shift	2	3.94±0.07	15.19	51.67	14.8 %
Evening Shift	2				
Night Shift	2				
Morning Shift	2	7.47±0.2	18.96	91.38	30%
Evening Shift	1				
Night Shift	1				

Table 5.3: 1hr arrival rate - Waiting times at the Triage for different nurses allocation.

It can be seen that for the 1hr Arrival rate and a nurse allocation in the shifts of 3-3-1, the Average Waiting time in the Triage for a patient is very small and it is  $2.15 \pm 0.03$  min. However, 6% of the incoming patients have to wait more than 10 min and in average 14.75 min. The results of the 3-3-1 nurse allocation were considerably better than of the other tested nurse allocations and therefore it is a good estimation of the needed number of nurses for the hourly arrival rate model. It has to be noted here again though, that since this arrival rate makes the model very congested, in reality the needed number of triage nurses would be less.

### 5.3.2 15min Arrival Rate

The same procedure was used for the 15min arrival rate model as well. The algorithm steps over the best found solutions (local optimas) are presented in *Figure5.11*.

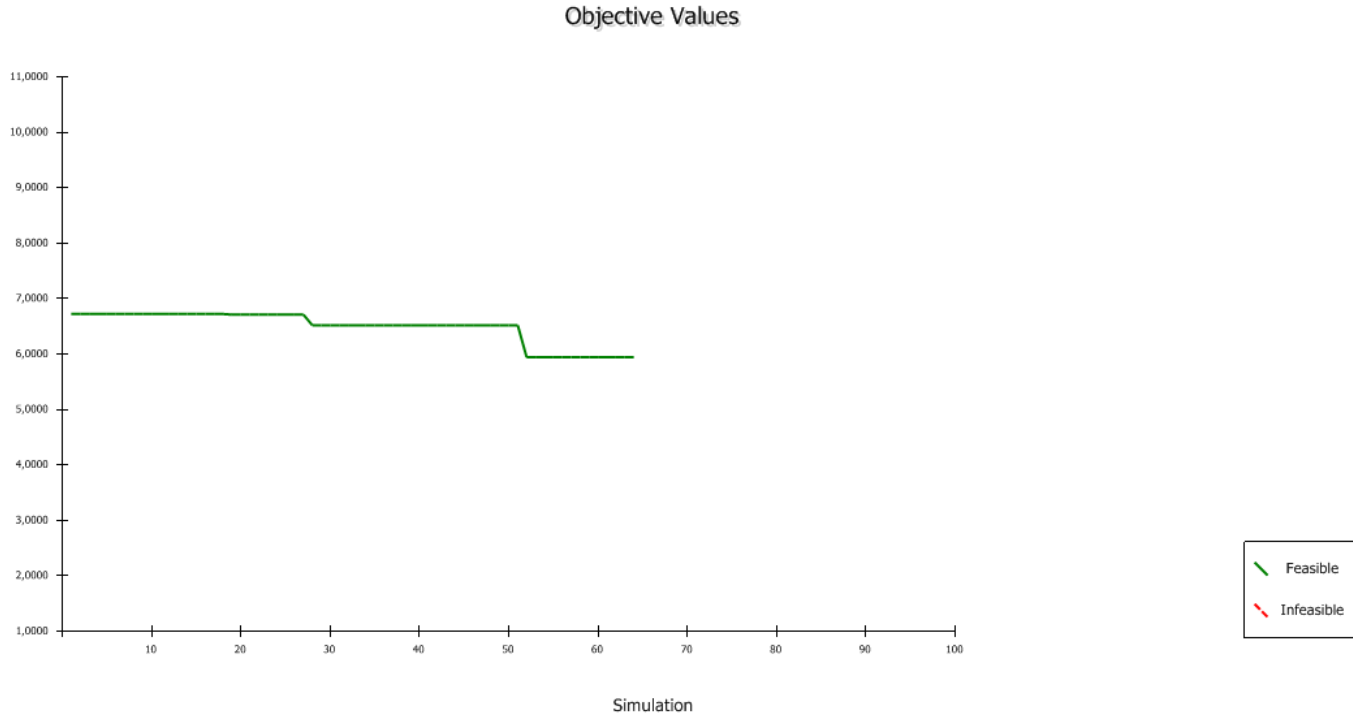


Figure 5.11: *15min Arrival - Best solutions found through the different iterations.*

The best solution according to the given objective, along with other found solutions were tested further and more relevant KPI's were gathered. The results are presented in *Table 5.4*. It can be seen that with the suggested solution (2-2-1 nurse allocation) the resulting KPI's seem very good (small waiting time for the patients etc.). However, the second (2-1-1) and the third solution (3-1-1) gave similar results as well, with the 2-1-1 even using even one nurse less. So, the 2-2-1 and 2-1-1 nurse allocations seem to be the most reasonable and effective ones.

Shifts	Nr.Nurses	Avg.Wait.Time	Avg.Max (>10 )	Max	Wait.Time>10
Morning Shift	2				
Evening Shift	2	0.94±0.04	12.94	40.43	2.1%
Night Shift	1				
Morning Shift	2				
Evening Shift	1	1.99±0.57	15.31	57.37	6.4%
Night Shift	1				
Morning Shift	3				
Evening Shift	1	1.75±0.59	16.52	77.87	6.2%
Night Shift	1				
Morning Shift	1				
Evening Shift	1	9.99±0.21	28.71	154.1	30.1%
Night Shift	1				

Table 5.4: 15min arrival rate - Waiting times at the Triage for different nurses allocation

### 5.3.3 Determining the final Arrival Model

From the previous results, an upper bound of the needed nurse allocation (3-3-1) was obtained from a congested model (1hr arrival rate) and a lower one (2-2-1 and 2-1-1) was obtained from a less congested model (15min arrival rate). In this section, these arrival scenarios will be tuned with their best found nurse allocation and tested further with the use of Arena's Process Analyzer. In that way, the arrival scenario which is going to be used at the following tests (e.g estimation of the needed number of 48hr beds), will be determined. The results of the Process Analyzer are presented in *Table 7*.

Scenario Properties		Controls				Responses		
Name	Reps	48hr Beds	M. Shift	Ev. Shift	N. Shift	Triage Avg. Waiting Time	48hr Avg. Waiting Time	48hr Beds Utilization
1hr (3-3-1)	4	75	3	3	1	2.15	27.99	0.7122
15min (2-2-1)	4	75	2	2	1	0.94	23.42	0.7115
1hr (2-1-1)	4	75	2	1	1	7.47	26.81	0.7102
15min (2-1-1)	4	75	2	1	1	1.99	23.21	0.7108

Table 5.5: Comparison of the different arrival models, tuned with their best nurse allocations.

It can be seen that with a 15min arrival rate, smaller triage waiting times were obtained and the process was more efficient, even with the use of less nurses. Since the patients go to the 48hr wards after the triage process, the efficiency of that stage influences the flow of the next one. For that reason and also because the 15min arrival rate represents better the real life's random arrival rate, the 15min arrival rate was decided to be used for all the next steps.

Furthermore, it can be noted that, for the same arrival rate and number of beds, as the average waiting time at the triage decreases, the arrival rate of patients at the 48hr ward increases, making the model there more congested and therefore patients have to wait more in order to be assigned a bed. For that reason, it is crucial to decide a good nurse allocation in the triage process before we proceed to the estimation of the needed 48hr bed. With a bad nurse allocation, the 48hr ward will be considerably less congested and therefore the resulting number of needed beds will prove to be less than the actually needed one. As good nurse allocations for the 15min arrival rate, the 2-2-1 and 2-1-1 can be considered. In order to optimize further the nurse allocation, the optimal number of nurses for each hour will be estimated, where possibilities in regards to overtime or to the use of different shifts will be examined.

### 5.3.4 Improvements on the estimated number of nurses

The mathematical model (1)-(2), was attempted to be optimized in regards to the needed number of nurses per hour. In *Table 5.6*, some of the given solutions are shown; those that provided both good results and more logical nurse allocations (that can be for example used with overtime etc.).

The hourly optimal allocations are very close to the shift-found ones (2-2-1 and 2-1-1). It can be seen that by using one less nurse at 22 p.m or between 21 p.m and 22 p.m in the 2-2-1 shift allocation, the waiting times are only increasing slightly. So, the cost (or time, since the nurse may work at other parts of the ED at that time) of one nurse can be saved for 2 hours every day. One additional cost-saving modification would be to have one nurse working in the first two hours of the morning shift instead of two nurses. It is obvious that the arrival rates in the beginning of the morning shift and in the end of the evening shift, are more similar to the night shift's one and therefore the model is less congested and fewer nurses are needed at these hours.

As the KPIs of the hourly nurses allocations are close to the shift-found ones, and it is unsure whether the suggested recommendations can be applied, (flex-time nurse, overtime in the night shift, or allocation of the nurse to other sections of the ED department), since only the hospital's decision maker's have the authority for such modifications, the present suggestions will not be used in the future steps of the model, but they can however function as future recommendations. For the next step, which the estimation of the needed number of 48hr beds, the 15 min arrival rate model with the 2-2-1 and 2-1-1 shift allocations will be used.

	Morning Shift														Evening Shift										Night Shift									
Hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	1	2	3	4	5	6										
Nr. Nurses	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1										
Avg.Wai.Time															0.97±0.05																			
Avg.Max (> 10)															12.95																			
Max															33																			
P(Wait.Time>10)															2.2%																			
N Nurses	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1											
Avg.Wai.Time															1.10±0.02																			
Avg.Max (> 10)															13.29																			
Max															41.3																			
P(Wait.Time>10)															2.8%																			
Nr. Nurses	1	1	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1	1	1											
Avg.Wai.Time															1.14±0.06																			
Avg.Max (> 10)															13.46																			
Max															46																			
P(Wait.Time>10)															2.9%																			

Table 5.6: 15 min arrival rate - Resulting KPIs for the different hourly nurse allocations.

## 5.4 Estimating the Number of 48hr Beds

In the present section, the needed number of beds in the 48hr ward will be estimated for the 15min arrival rate model using the 2-2-1 and 2-1-1 nurse allocation. Then, the results of these allocations are compared in order to decide which nurse allocation will be used. Different number of beds are then analyzed further for the chosen shift allocation such as a final estimation of the needed number of beds will be made.

Using Arena's OptQuest and a feasible range of 70-82 beds the following objective, (3), was attempted to be optimized and the avg.waiting time was calculated for each number of beds. The best found solutions through the algorithm's iterations are presented in *Figure 5.12*, where it can be seen how much the avg.waiting time decreased as the number of beds increases.

$$\text{Minimize : Avg.. Waiting time at the 48hr Wards} \quad (5.3)$$

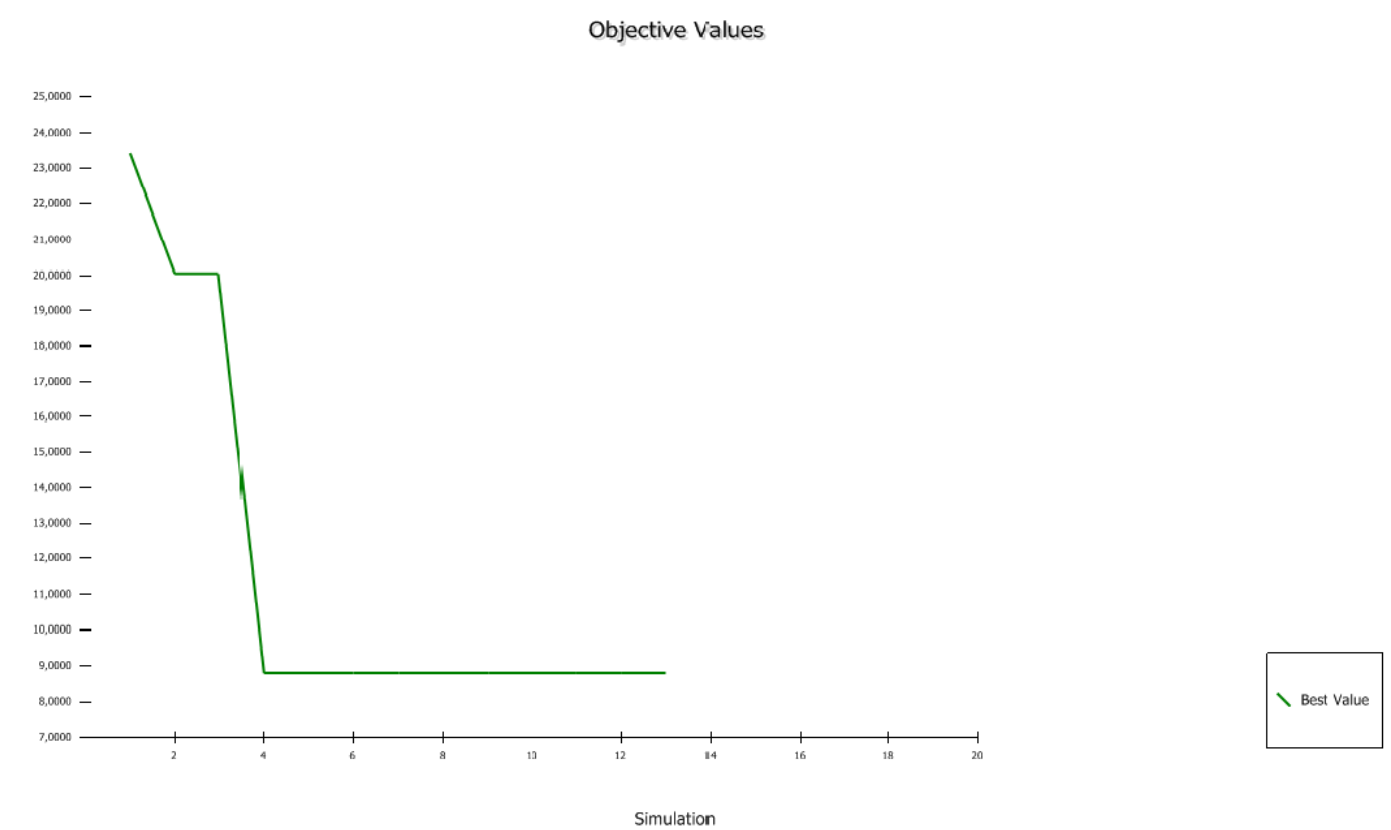


Figure 5.12: 2-2-1 nurses, 48hr bed optimization - Best solutions found through the different iterations.

However, the resulting average waiting time at the 48hr beds cannot be used as a sole criterion for the decision of the needed number of beds; therefore, more KPI's were gathered, regarding the Avg.Maximum Waiting time and the beds' average utilization for all the tested number of beds. The results for the 2-2-1 and 2-1-1 nurse allocations are presented in *Table 5.7* and *Table 5.8*, respectively.

Nr of Beds	Avg.Wai.Time	Avg.Max	Utilization
82	8.81±0.56	9.33	65.3%
81	9.64±0.3	9.82	66%
80	11.45±1.3	12.46	66.7%
79	13.25 ± 1.55	14.11	67.6%
78	15.49±0.94	16.26	68.5%
77	17.76±0.7	18.15	69.5
76	20.06±1.25	21.22	70.5%
75	23.42±1.76	25.02	71.1%

Table 5.7: 2-2-1 nurses, resulting KPIs for different numbers of 48hr beds.



Nr of Beds	Avg.Wai.Time	Avg.Max	Utilization
82	8.4±1.26	9.1	65%
81	9.77±0.72	10.44	66%
80	11.69±1.13	12.29	66.8%
79	13.14±0.58	13.37	67.6%
77	17.431±23	18.1	69.3%
76	20.22±3.16	21.93	70.2%
75	23.21±2.31	24.47	71%

Table 5.8: 2-1-1 nurses, resulting KPIs for different numbers of 48hr beds.

From the tables above, it can be noticed that for the same number of beds, the resulting time and utilization-related KPI's are not just similar for both of the nurse allocations but in the 2-1-1 are even smaller, since, as it was previously explained in section 5.3.3, the flow in that way is more balanced between the Triage and the 48hr bed departments. Moreover, since the 2-1-1 nurse allocation uses one nurse less, relevant costs are saved for the hospital as well. For all the above reasons it was decided that the further analysis will be based on a model with a 15min arrival rate and a 2-1-1 nurse allocation.

From *Table 5.8* it can be seen that the number of beds in the range of 79-82 resulted in small average waiting times and in average beds' utilization close to the desired number of 66%. So, these number of beds will be compared further in regards to how often and how much the desired utilization of 66% is exceeded along with the average waiting times for each triage type patient. By doing so, a more robust suggestion on the needed number of beds could be made.

The number of times along with the respective probability of surpassing the average utilization of 66% is presented in *Table 5.9* for the chosen range of beds.

Nr.Beds	Times/year	P(Utilz. > 66%)
82	185	0.5%
81	203	0.6%
80	201	0.6%
79	226	0.62%

Table 5.9: Utilization > 66% KPIs for the chosen range of beds.

From the above table it can be seen that although the average utilization differs, the probability of exceeding the 66% utilization is very small through all the number of beds. For example, with 79 beds, only 0.62% of the time the beds utilization exceeds the 66% limit.

So, since according to the utilization KPIs the performance of the different number of beds is similar, more statistics were gathered in regards to the average waiting times at the 48hr wards for each triage patient type. The results are presented in *Figure 5.13*.

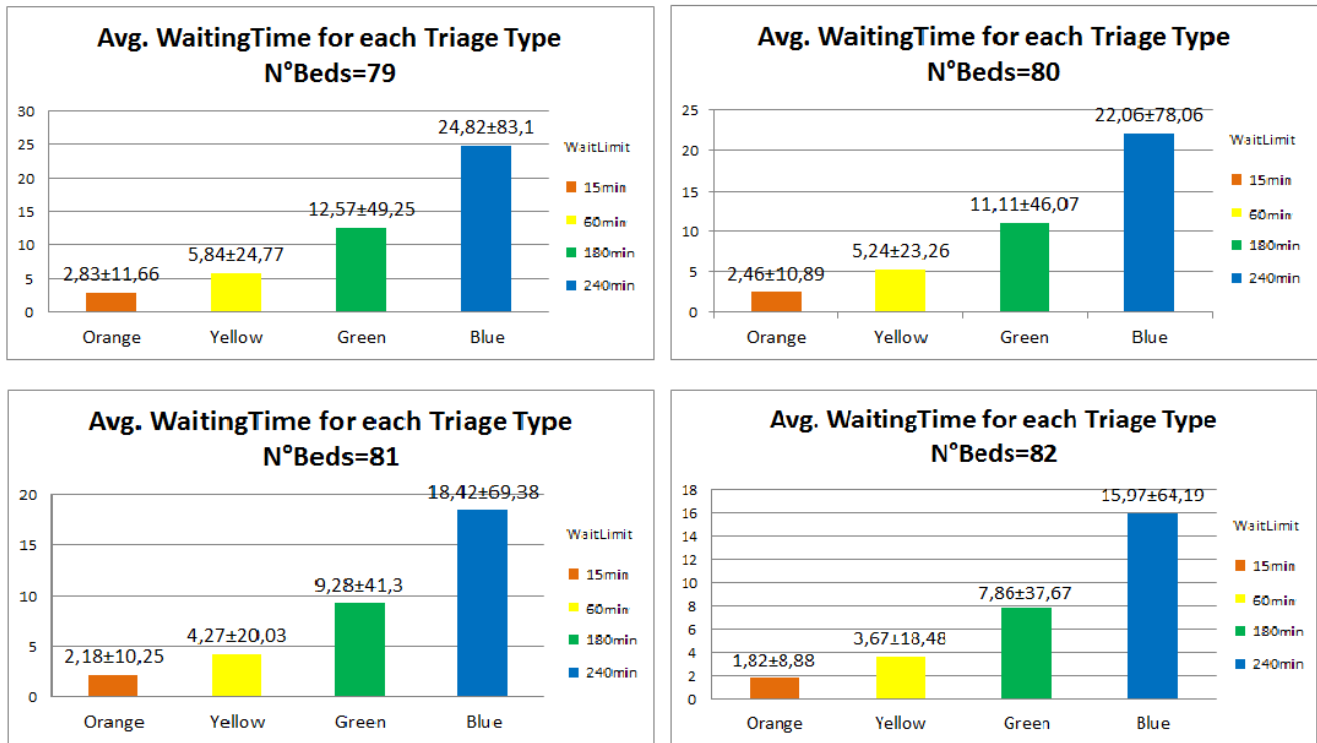


Figure 5.13: Average waiting time of each triage type patient for different number of 48hr beds.

As stated previously, the time limit within which each patient type has to be assigned a bed is considered to be equal to the time limit he has to be seen by a doctor (although in reality for some patients the treatment might start before being assigned a bed). Therefore, orange, yellow, green and blue triage-type patients have to be assigned a 48hr bed within 15min, 60min, 180 and 240min respectively. It can be seen that, for all the selected number of beds, every patient type waits in average (regarding also the standard deviation) considerably less than his waiting limit. So, all the candidate numbers of beds seem to perform well under this criterion.

However, even if the waiting times are not exceeded when the standard deviation is taken into account, in reality some patients might still wait more than their limits. This can be explained from the way the standard deviation is calculated; a lot of patients have a waiting time close or equal to 0 whereas few of them exceed the waiting limits. So, according to statistics since the 0-time patients are more, the calculated standard deviation does not depict the maximum waiting time for each patient type.

Therefore, the given beds range was compared further in regards to how often and how much a

patient has to wait more than his waiting limit. The results are presented in *Table 5.10*, where Avg>Limit represents the average waiting time of all the patients that wait more than their limit and % is the percentage of how many of them exceed their waiting limit.

	<b>82</b>		<b>81</b>		<b>80</b>		<b>79</b>	
	Avg>Limit	%	Avg>Limit	%	Avg>Limit	%	Avg>Limit	%
<b>Orange, Wait<math>\leq</math>15</b>	39.04	3.7%	41.22	4.30%	40.52	4.90%	41.11	5.70%
<b>Yellow, Wait<math>\leq</math>60</b>	113.38	2%	113.62	2.40%	121.47	2.90%	121.52	3.30%
<b>Green, Wait<math>\leq</math>180</b>	266.05	1.40%	266.48	1.70%	276.08	2.10%	274.06	2.50%
<b>Blue, Wait<math>\leq</math>240</b>	346.22	2.70%	350.78	3%	365.91	3.50%	367.35	4.20%

Table 5.10: Waiting Time > Limit KPIs for each triage type of patient in the chosen range of beds.

It can be seen that the patients' *Avg>Limit* is quite large; however, the probability of a patient waiting more than his limit is very small for all the tested range of beds. And of course, it is natural that sometimes the hospital might prove to be small enough to efficiently treat all the incoming patients (e.g. sudden snowstorm or earthquake).

For all the above reasons, a number of beds in the 48hr wards between the tested range (79-82) seems to be a reasonable suggestion. However, if the desired bed utilization of 66% is taken into account along with the fact that the 15min arrival rate makes the model probably more congested than reality and considering also the beds' cost and the space requirements for each bed, the most suitable suggestion for the current model seems to be 80 beds.

# Chapter 6

## Final Results

In this last chapter, the final results for the 15min arrival model, tuned with the suggested nurse allocation of 2-1-1 and 80 beds in the 48hr wards are presented.

Moreover, the results gathered from different scenarios are discussed. Those models, as the previous and final one, run for 4 years so as more reliable statistics will be gathered.

### 6.1 KPIs

After the simulation comes to an end, Arena automatically shows all the significant results concerning the model's performances.

Those are presented in the current section, divided into three categories, regarding the *number of patients*, *Queue situation* and *resources*.

#### 6.1.1 KPIs regarding the number of patients

It can be noted here that the number of patients may not be exactly equal to the expected one (for example in the model, on average 24.9% of the patients go to the wards instead of the 21.15% of the 2011-2012's actual given data). However, this is something that cannot be controlled due to statistics and since the model is simulated for 4 years it is of course more realistic to have some numbers differing between the years.

On average, every year 45362 patients are coming into the ED (since the simulation is continuous in the 2nd, 3rd and 4th year there are also patients from the previous year). So, around 45356 are annually exiting the system, since at the moment the simulation terminates some patients may still be in the system (for example, occupying a bed).

The average number of patients along with the half width, for each triage color can be seen in *Figure 6.1*. It can be observed that although the input data have been already "cleaned" from the patients who do not need a bed for their treatment (who are more likely to be blue type ones), the biggest percentage of the incoming patients is of Blue and Yellow triage colors, in accordance to the given input data in *Table 4.6*, as expected.

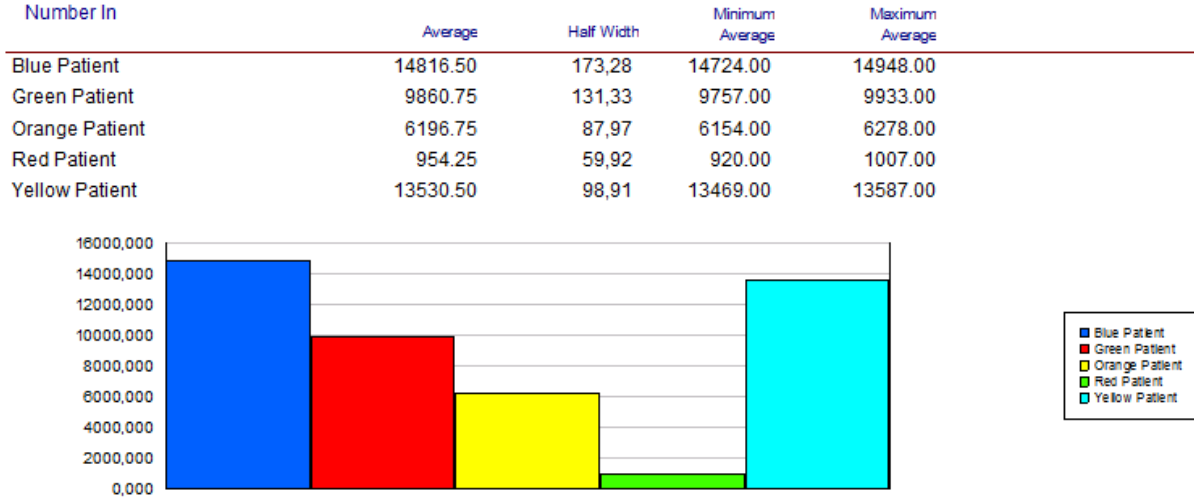


Figure 6.1: *Average annual number of incoming patients for each triage type.*

From the annual incoming patients, in average  $33078.25 \pm 101$  are going to the ED's 48hr beds. The rest of them, around  $11344 \pm 75.75$  are going straight to the Wards with 29% of them ( $3285.5 \pm 29.81$ ) having to stay at the ED because the wards are closed at that time, where they stay either until they are cured or until the wards open again. Moreover, of the ED patients at the 48hr beds on average 29.6% of them ( $9784.5 \pm 69.11$ ) have to go the Wards for further treatment. From those, 22.1% ( $2165.25 \pm 58.06$ ) are about to go to the Wards during the night and therefore they keep occupying their bed in the 48hr department, until the Wards open. The discussed numbers are shown in *Figure 6.2*.

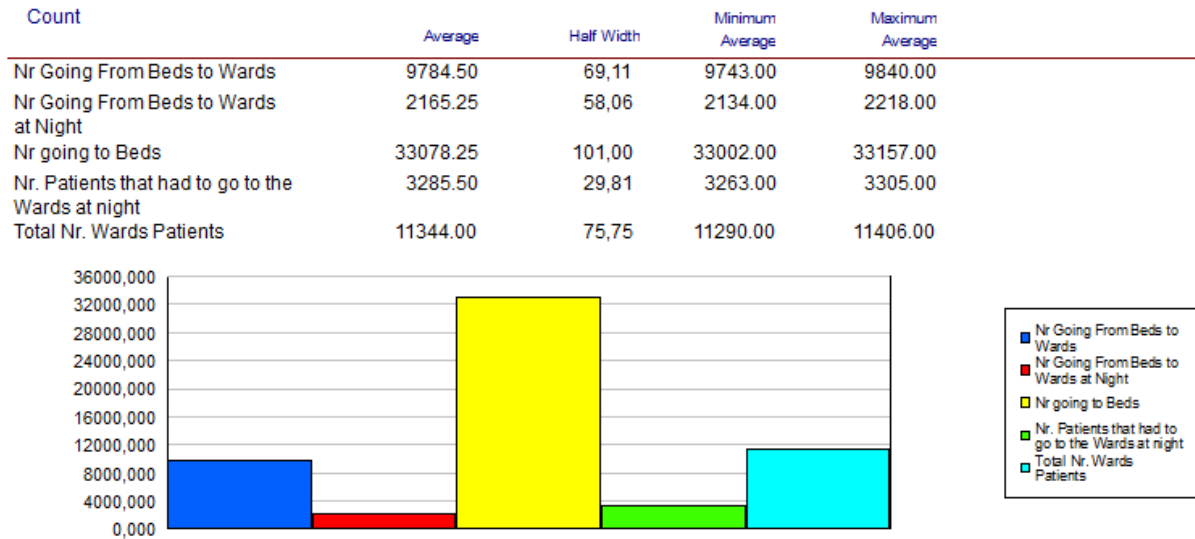


Figure 6.2: *KPIs on the annual number of Ward and 48hr bed patients .*

### 6.1.2 KPIs regarding the Queue situation at the system's processes

All the relevant waiting times, also discussed previously in the decision regarding the 2-1-1 nurse allocation and the use of 80 beds in the 48hr ward, are summarized in *Figure 6.3*. It can be noted here that some waiting times slightly differ from the respective ones calculated before. However, this can be explained from the simulation's genuinely statistical behavior. It can be seen that with the current tuning, the patients do not have to wait for a long time to be served (which is also reflected in the number of patients waiting in each queue) and therefore, a balanced flow within the system is secured.

Queue				
Time				
Waiting Time	Average	Half Width	Minimum Average	Maximum Average
48hrs Ward.Queue	11.6888	1,13	10.8455	12.2850
Process Triage.Queue	1.8567	0,57	1.6232	2.3810
Reception Health Card.Queue	0.9143	0,01	0.9052	0.9224
Other				
Number Waiting	Average	Half Width	Minimum Average	Maximum Average
48hrs Ward.Queue	0.8093	0,08	0.7493	0.8512
Process Triage.Queue	0.1569	0,05	0.1371	0.2013
Reception Health Card.Queue	0.07723431	0,00	0.07637900	0.07791868

Figure 6.3: *KPIs on the system's queue situation .*

### 6.1.3 KPIs regarding the system's resources

The collected KPI's for the system's resources (Reception Nurse, Triage Nurses and 48hr beds) are presented in *Figure 6.4*.

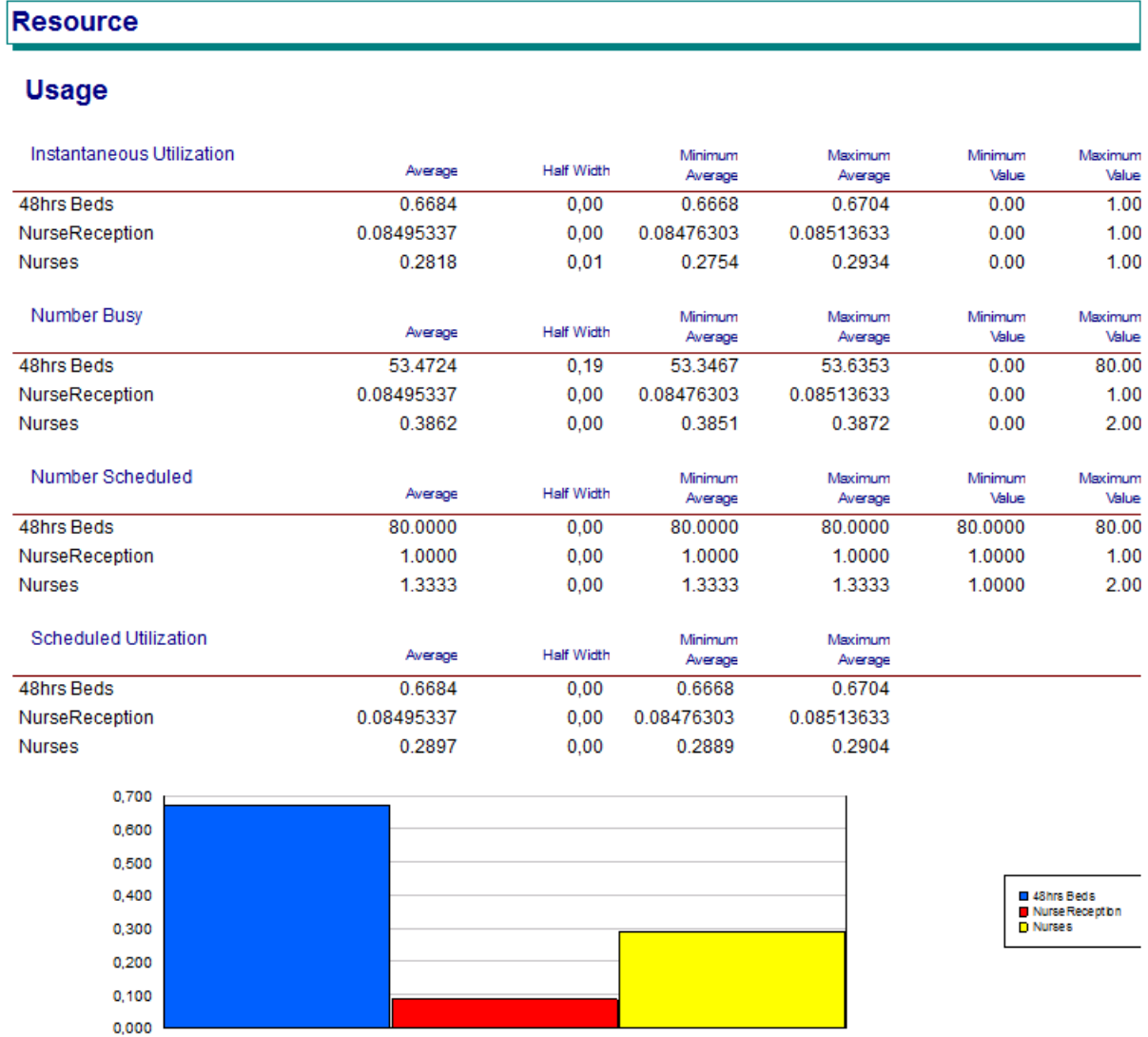


Figure 6.4: *KPIs on the system's resources* .

It can be seen that the 48hr beds' average utilization (instantaneous and scheduled) for the used number of 80, is the one calculated in the previous section. An additional graph, showing the utilization's distribution can be seen in the *Appendix*. It can be noted here that the presented nurses'



utilizations would be higher in real life, where the patients enter the system randomly during the whole hour, and so the nurses would serve patients during the whole hour and not every 15 min.

The Number Busy shows how many resources are used in average during every minute of the simulation (for example, in average, 53 beds out the 80 are continuously occupied).

## 6.2 Different Scenarios

In this section, the performance of the previously suggested number of resources is tested under different scenarios, in order to estimate how assumptions have modified the outputs of the final model. Firstly the arrival rate is modified (+10%, +20%) and secondly the assumption that the wards are closed at night is removed. Finally a scenario with transportation times different than zero is considered to analyze how this assumption could effect the final model. The model's behavior under these circumstances is analyzed and additional suggestions are consequently made.

### 6.2.1 Changing the Arrival Rate

As stated previously, different arrival rates have been performed in order to evaluate the system's most important KPIs, such as the effectiveness of the designed ED in the case of increased arrivals will be tested.

It is important to note here that the increase in the arrival rate of course does not usually take place through the whole year but it rather happens during a short period of time, for example one week or a particular day, triggered by unexpected causes such as an epidemic burst, severe weather conditions etc., making therefore the model more congested than usual.

Since these events have a random behavior and cannot be predicted, it was decided to extend this scenario throughout the year making the model more generic and not modifying the input data. However, on average, the annual results should be similar to those of one day or week. So, by analyzing the results of an annual increase we can also draw some conclusions on the model's behavior in such busy days or weeks.

The 15min arrival rate model was used, tuned to the suggested resources of 2-1-1 nurses and 80 beds. The results of an annual increase in arrival rate by 10% and 20% are shown in *Table 6.1*

Scenario Properties		Responses			
Arrival Rate	Reps	Triage Waiting Time	48hr Waiting Time	48hr Nr in Queue	Beds Utilization
15min	4	0.93±0,04	11.45±1,3	0.79±0,09	0.67
15min +10%	4	2.37±0,98	32.56±2,15	2.47±0,17	0.73
15min +20%	4	2.73±0,84	77.02±2,0	6.36±0,17	0.80

Table 6.1: 2-2-1 nurses, 80 beds, performance under different arrival rates.

It can be noticed that the Avg.Waiting Time at the Triage process is not particularly effected by the arrival changes, (since it still remains small and much lower than 10 min), whereas the Avg.Waiting Time at the 48hr department along with the beds' utilization change considerably. This can be explained by bearing in mind their different processing times: in the Triage process it has values (according to the different Triage types) between 2 and 7 minutes with a std.dev of around 3 min; the 48hr ward, instead, has processing times (according to the pathology group) around 9 hours with one hour of std. dev. So, there would be more patients in the queue waiting for a bed to be available for a longer time; and this is also reflected on the beds' utilization.

However, from the above results, it seems that the ED could be able to tolerate a 10% increase of incoming patients with the suggested number of resources, even though all the KPIs are 3 times bigger compared to those of the regular arrival rate. The beds utilization of 73% still permits periods of maintenance, and the waiting time at the 48hr Beds is not too large.

As far the 20% increase is concerned, the resulting KPIs are 7 times bigger than the regular ones, and an average waiting time at the 48hr beds of 77 minutes could badly effect the ED's performance; this is also reflected on the number waiting and in the beds' utilization. A utilization of 80% could be probably tolerated for few days but not for more.

## 6.2.2 Wards open at night

In the present section, the assumption that the wards are closed at night has been removed, since it would be interesting to see how the model would perform if this would happen (although having all the wards open at night is not realistic due to internal planning reasons). Of course, some of them could open instead of all of them, (for example the Ward receiving most of the Y patients which seems to be the busiest one); but, since no information regarding the feasibility of such an alternative was given, the tested scenario would be that all of the Wards are open at night. That means, that the total average number of 5451 patients (see *Figure 6.2* that stayed in the system because the wards were closed, will in this case, be instantly disposed from the system.

*Figure 6.2* shows how this change affects the current model, regarding the avg.waiting time at the 48hr Wards, the avg. number waiting and the beds' utilization (no KPIs are presented about the Triage process, since the Triage process is not affected by any of the Wards' modification).

Since with the Wards open, the system is less congested, different numbers of 48hr beds were also tested such as a similar performance of the "Wards closed-80 48hr beds" one could be achieved with the use of less beds. It can be seen that, under the assumption that the Wards are open at night, a reasonable number of 48hr beds is 70, which results in small waiting-KPIs and in a utilization of 66%, as the requested one is.


KPIs	Nr of Beds			
	80	75	71	70
Avg. WaitTime 48hr	6,29±0,62	13,12±1,77	22,1±1,1	24,46±1,08
Avg. Nr Waiting	0,4±0,04	0,83±0,12	1,39±0,07	1,54±0,07
Beds Utilization	57.80%	62%	65%	66%

Table 6.2: Wards open at night - KPIs for different numbers of 48hr beds.

### 6.2.3 Transportation Times

In this section the assumption that the handling times between processes were set equal to zero has been deleted.

Different times have been performed in order to assess to what extent the assumption has changed the results. In *Table 6.5* all the used transferring times are listed; each value is given as a normal distribution (mean and standard deviation), considering that this kind of distribution better represent the behavior of a real process.



TRANSFERRING TIMES		
From	To	Value
Entrance	Reception	NORM(0.5,0.8)
Reception	Triage	NORM(1,0.3)
Triage	48hr	NORM(2,0.6)
48hr	Wards	NORM(1.5,0.3)
48hr	Exit	NORM(3,1)
Entrance	48hr	NORM(3,0.6)

Figure 6.5: *Times between processes.*

Running the model considering those distribution, the model KPIs, compared with the final ones presented in *Chapter 6*, confirm that the made assumption doesn't effect significantly the output of the model.

In *Figures 6.6, 6.7, 6.8* the most relevant KPIs are shown regarding the waiting time, the number waiting and the resources' utilization.

Number Waiting	Average	Half Width	Minimum Average	Maximum Average
48hrs Ward.Queue	0.7747	0,06	0.7454	0.8252
Process Triage.Queue	0.1832	0,06	0.1549	0.2401
Reception Health Card.Queue	0.05331961	0,00	0.05297235	0.05366128

Figure 6.6: *Number waiting.*

Waiting Time	Average	Half Width	Minimum Average	Maximum Average
48hrs Ward.Queue	11.2056	0,81	10.7867	11.9130
Process Triage.Queue	2.1695	0,74	1.8349	2.8430
Reception Health Card.Queue	0.6313	0,01	0.6271	0.6358

Figure 6.7: *Waiting Time.*

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average
48hrs Beds	0.6673	0,00	0.6654	0.6698
NurseReception	0.08475411	0,00	0.08468093	0.08483517
Nurses	0.2831	0,01	0.2752	0.2957

Figure 6.8: *Resources' utilization.*

It can be easily seen that, as explained before, the KPIs do not undergo relevant changes; besides, they are even smaller. This can be explained as follows:

- Due to statistical reasons, different outputs can be obtained from running several times the same model: every run has its results and they will be different from each-other.
- Using transportation times between processes, the system is less congested; patients arrive more fluently to the different stages of the model. This is more reflected on the *number waiting* and the *waiting time*.

However, since the considered transportation times were simply supposed and no-data were given about it, it has been decided to not use them in the final model. Besides, without them, the model is more congested (even if the different is minimum) and it increases its reliability.



## Conclusion

In the present report, the Bispebjerg's ED was simulated using the input data provided by the Hospital. As far as the arrival data is concerned, it was referring to the number of patients coming every hour for a whole year and therefore the model was more congested than reality, since all the patients were arriving in the beginning of each hour. So, the given arrival rate per hour was interpreted also to a half an hour one (30min) and to a quarter one (15min) and the respective resulting models were compared. Then, an upper (3-3-1) and a lower bound (2-2-1 and 2-1-1) of the needed number of triage nurses were obtained by using the 1hr arrival model and the 15min one respectively. The results were compared and it was decided to use the 15min arrival rate model for the further simulation steps since it was closer to reality. Moreover, improvements regarding the nurse allocation were made by estimating the optimal number of needed nurses for each hour instead of each shift.

Then, the needed number of 48hr beds was calculated for the 2-2-1 and 2-1-1 nurse allocation, such as the waiting time at the 48hr wards will be minimized and the desired 66% beds' utilization will be achieved. After deciding to work further on only with the 2-1-1 nurse allocation, (since in relation with the beds it provided a better and more realistic system flow), different numbers of beds within the suggested range were tested and compared in regards to more KPIs (such as avg. waiting time of each triage-type patient, probability of exceeding the 66% beds' utilization, etc.) Therefore, the suggested number of 48hr beds proved to be 80.

So, for the 15min arrival rate model, the 2-1-1 triage nurse allocation in each shift, along with the use of 80 beds in the 48hr ward, seem to comprise a logical suggestion. However, in reality, the needed number of resources may be different as the system is more complex, some of the assumptions may not hold and the arrival rate is not the same. Some of the possible different scenarios were also taken into account and the suggested model's performance was evaluated.

For future work, instead of an hourly arrival rate, an arrival rate that refers to a smaller time interval (e.g 5-10 min arrival rate) or a real-time one, (for example extracted from the time information of the triage-filled forms) should be better used. Moreover, information on the potential transportation times and on the actual triage assessments time for each type of patient could be gathered. Additionally, the correlation between the probability of being a specific pathology type patient and a triage-color one could be known, such as the time that a patient occupies a 48hr bed would differ depending on his severity index value (given by the triage color). Furthermore, in case of ward-type patients having to spend the night in the ED, their treatment time could be

known. Moreover, additional resources could be integrated in the system (doctors, nurses at the 48hr beds) if relevant information was provided. Finally, the time that a bed becomes available in the IT system after its actual release could be also used in the model. From the above, the resulting simulation will be even closer to reality and more accurate suggestions could be made. However, it is of course extremely complicated to gather so much detailed information from such a complex system as the ED one. Moreover, it requires resources and a lot of time to intensely gather such a big amount of data [19]



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# Appendix

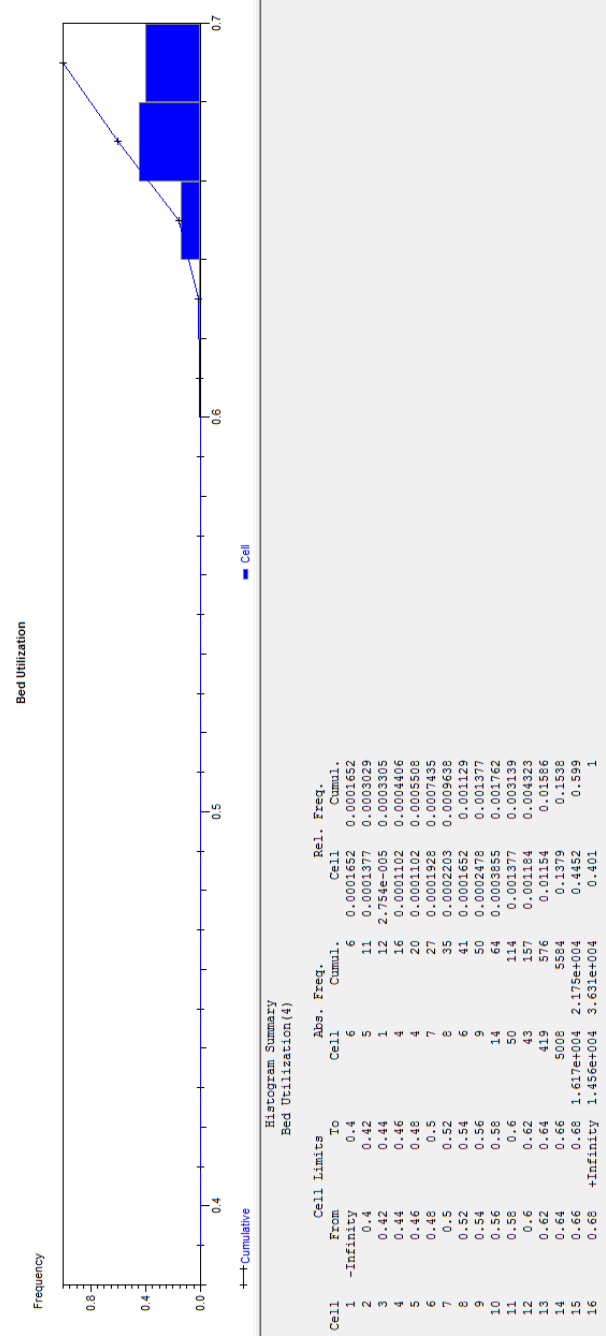


Figure 6.9: 80 48hr beds - Utilization's distribution .