THE 6TH INTERNATIONAL WORKSHOP ON INNOVATIVE SIMULATION FOR HEALTH CARE

SEPTEMBER 18 – 20, 2017
BARCELONA, SPAIN

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PRINTED IN RENDE (CS), ITALY, SEPTEMBER 2017

ISBN 978-88-97999-97-3 (Paperback)
ISBN 978-88-97999-89-8 (PDF)

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ISBN 978-88-97999-89-8 (PDF)

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CHAIR'S MESSAGE

WELCOME TO IWISH 2017!

In the awesome setting of Barcelona, we are glad to welcome all the participants to the 6th edition of the International Workshop on Innovative Simulation for Healthcare (IWISH 2017). The formula of having, as part of the I3M Multi-conference, a workshop aiming at bringing together scientists from engineering, natural and life sciences to stimulate discussion on new methods and topics in the emerging fields of healthcare has been found to be successful. Therefore, thanks to the incredible efforts of the whole Organization Committee, the opportunity to focus on Modeling & Simulation technologies applied to health systems and on different healthcare-related issues and problems is renovated and offers researchers, practitioners and delegates of several institutions from all over the world the chance to discuss about latest advances and huge challenges in healthcare systems.

As even highlighted in the papers included in the present proceedings, in recent years, healthcare systems are facing huge challenges caused by new diseases, demographic changes, medical accidents and rising costs. Indeed, healthcare is nowadays a major research area where the use of modelling and simulation based approaches can be regarded as an excellent tool for investigating and solving complex problems including, among others, the spread of diseases, analysis of biological systems, organization of healthcare processes, resource optimization, scheduling of activities, etc.

The interdisciplinary nature of IWISH fosters a seamless integration of life science and new technologies: only a full integration of these two opposite aspects will provide new advances in research and real world applications.

To conclude, we would like to thank also our sponsors, all the authors (for submitting their works) and the invaluable works made by reviewers. We are all contributing to make IWISH a truly great conference that grows year by year.

Marco Frascio
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ACKNOWLEDGEMENTS

The IWISH 2017 International Program Committee (IPC) has selected the papers for the Conference among many submissions; therefore, based on this effort, a very successful event is expected. The IWISH 2017 IPC would like to thank all the authors as well as the reviewers for their invaluable work.
A special thank goes to Prof. Miquel Angel Piera from Autonomous University of Barcelona, as Local Organizer and to all the organizations, institutions and societies that have supported and technically sponsored the event.

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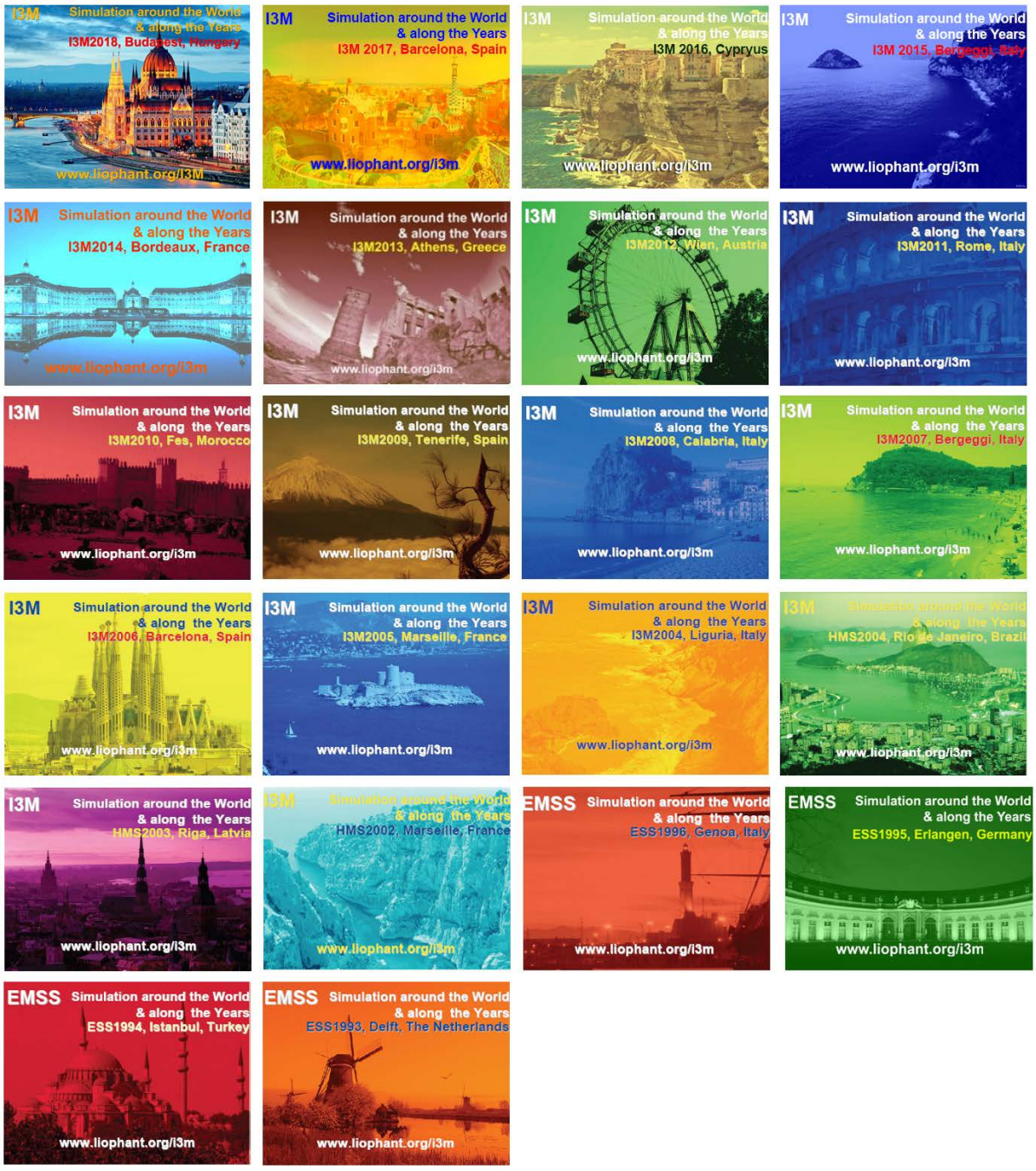

ISBN 978-88-97999-89-8; Bruzzone, Frascio, Longo and Novak Eds.

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ISBN 978-88-97999-89-8; Bruzzone, Frascio, Longo and Novak Eds.

QUALITY ASSESSMENT OF INPUT DATA FOR EMERGENCY DEPARTMENT SIMULATION

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ABSTRACT

Emergency Departments (EDs) constitute an important component in a healthcare system. Recently, they are confronted with a substantial growth in demand. Combined with the ever tightening budgets, this has led to the problem of overcrowding in many EDs. Simulation has been widely used in operations management research for analysing and improving patient flow in EDs. The quality of input data is of great importance to build a realistic simulation model. In this paper, data quality problems in healthcare records of emergency departments are identified based on a case study in a Belgian university hospital. The problems are categorised and data quality assessment techniques are developed for each category. A combination of quantitative and qualitative metrics is described to estimate the potential impact of the data quality issues on simulation.

Keywords: data quality problems, data quality assessment, simulation, emergency departments, electronic health records

1. INTRODUCTION

Emergency Departments (EDs) constitute an important component in a healthcare system. They are one of the main entry points of a hospital, offering non-stop healthcare services to patients with various needs. From a social point of view, it is crucial that EDs work efficiently, since timely and good services can save lives. However, EDs are large, complex and dynamic units which are difficult to manage. Moreover, EDs are confronted with a substantial growth in demand due to the ageing population and the trend toward utilising the ED for non-emergency care. Combined with the ever tightening budgets, this has led to the problem of (over)crowding in many EDs. Overcrowding occurs when the demand for emergency services exceeds the available resources in the ED (Bergs et al. 2016, Carmen and Van Nieuwenhuyse 2014).

Currently, ED overcrowding is considered a major international problem. It has significant consequences for both patients and caregivers (Bergs et al. 2016). A lack of sufficient resources prevents timely and suitable services, leading to increased length of stay of patients, increased waiting times, patient dissatisfaction, increased probability of patients leaving the ED without treatment and increased stress levels of caregivers. To face these challenges hospital managers are continuously exploring opportunities to improve the efficiency of their healthcare system without reducing the quality of care (Ahmed and Alkhamis 2009, Carmen and Van Nieuwenhuyse 2014).

Operations Research and Operations Management (OR/OM) techniques have been widely applied to analyse and optimise processes in healthcare organisations (e.g. Saghafian et al 2015). Since EDs are complex and stochastic systems, leading to stochastic outputs, the complete system cannot be modelled analytically and the stochastic outputs can only be evaluated through simulation. Simulation also makes it possible to investigate the simultaneous effect of different improvements. In this way, the simulation model can take interdependencies into account. Moreover, it is possible to analyse and optimise different measures of emergency department performance.

The first step in a simulation analysis is to build a realistic simulation model. In this respect, two key issues have to be considered that have an impact on the extent to which the model reflects reality. First of all, patient flow through the ED results from the interplay of many factors, so modelling the ED as a whole gives a more realistic view. Most simulation models of an ED focus on the treatment phase, while patient flow through an ED consists of three phases: inflow, throughput (or treatment) and outflow (Asplin et al. 2003, Saghafian et al. 2015). The inflow part is the arrival process in the ED. Arrivals are either by ambulance or by patient walk-in. The treatment part consists of triage, registration, placement in an ED bed, clinical assessment, treatment and diagnostic testing. The last part of patient flow, the outflow, is the disposition process. A patient can be discharged, kept under observation or admitted to an inpatient unit (Carmen and Van Nieuwenhuyse 2014, Gul and Guneri 2015). Modelling all three parts makes a simulation model more realistic, but only if there is sufficient and error-free information available for all three phases. Therefore, the second important issue is the quality of the data used as input to the simulation model. The Garbage-In Garbage-Out principle states that the

ISBN 978-88-97999-89-8; Bruzzone, Frascio, Longo and Novak Eds.

input data used has a direct effect on the quality of process analysis and improvement (Mans et al. 2015, Oliveira et al. 2005).

Data acquisition, data quality assessment and data quality improvement are three necessary steps preceding the construction of a simulation model. Data can be acquired through interviews, observations, surveys or electronic health records (EHRs). Previous research on simulation in EDs does not take data quality into account or lacks a description of the data cleaning process. This paper focuses on data quality assessment of input data extracted from the electronic health records (EHRs) of an emergency department. Since EHRs are frequently used as input data in ED simulation studies, there is a need for a structured approach in assessing the quality of this data. The purpose of this paper is to clarify the problem and importance of data quality in operations research. Based on a case study in a Belgian university hospital, data quality problems faced in the EHRs of an ED are identified and a framework for categorising these problems is developed. A combination of quantitative and qualitative measures is proposed to assess the extent of the data quality problems in each category. The framework in combination with the assessment methods provides guidance to researchers for inspecting input data before use. The data acquisition process and quality problems with regard to database development and improvement are beyond the scope of this paper.

2. PROBLEM CONTEXT

This paper is based on data extracted from the EHRs of the ED of a Belgian university hospital. The hospital under study is confronted with ED overcrowding, caused by an increase in the number of patient visits without a proportionate capacity expansion. The total number of visits to the ED approximated 57.650 in 2016 and is expected to increase in 2017. As simulation is an effective tool for the analysis and improvement of ED operations (Oh et al. 2016, Saghafian et al. 2015), the final goal is to build a realistic simulation model of the ED. The extracted data file will be used as input to this model. The file contains anonymised patient records for all patients that visited the ED in November 2016, December 2016 and January 2017. The first step, before building the simulation model, is to assess the quality of this data file as input to the simulation model.

EHRs are used throughout the entire hospital to standardise data gathering and to facilitate data exchange between departments. The software used for the EHRs captures the medical information of every patient and his flow throughout the hospital. Each patient has its own record with a unique patient number in the database. Patient records in the ED contain personal information, mostly obtained by read-in of the identity card. Furthermore, medical and patient flow information is registered at every stage in the ED. This information contains, amongst others, symptoms, diagnosis, type of inflow, timestamps of the patient flow through the ED, outflow destination, etc. Some data is gathered automatically due to triggers in the system, e.g., if a CT-scan is ordered, a timestamp of the order is automatically added to the patient record. Other information has to be inserted manually by a physician, nurse or administrative clerk such as the triage code of patients and the diagnosis. EHR data registration is a process in which individuals with a wide range of backgrounds, all working in the ED, are involved. They all attach different importance to data registration and the precision of the data inserted into the system (Kahn et al. 2012). Additionally, data registration is not the primary focus of healthcare providers. This makes the intrinsic quality of data in EHRs questionable. In assessing the quality of the extracted data file, the primary focus of this paper is on its suitability as input for the simulation model. The data has to be qualitative enough for reuse in the operations research domain. Otherwise, the results of the research can be misleading and of little value. The fitness for use concept indicates that data can be suitable for one research area or for one type of stakeholders, but of low quality for another. Patient data are recorded for operational and managerial purposes inside the hospital (e.g. monthly overviews using scorecards and personnel assessments) and for clinical research. They are not gathered with a focus on reuse in the operations management domain (Kahn et al. 2012, Wang and Strong 1996, Weiskopf and Weng 2012).

Data quality assessment is essential to appraise the intrinsic quality and fitness for use of the extract from the EHRs as input data for the simulation model. Data quality assessment is preceded by the identification of potential data quality problems. If problems are identified, their extent and impact can be assessed by using quantitative metrics and expert judgement (Kahn et al. 2012, Pipino et al. 2002)

Based on the dataset on one hand and on-field observations and interviews on the other hand, data quality problems present in the EHRs of the ED are identified in this paper. The focus lies on data quality problems with a potential impact on simulation results. To this end, quality issues concerning the input data required in the simulation model are the main focus. The input data needed for the simulation model depend on the software and process model used. The simulation model will be built in Arena, a discrete-event simulation software provided by Rockwell Automation. Some of the necessary input data in the Arena software include: durations of service times, patient arrival times, patient categories and processing rules, resources and their capacity etc. (Guo 2016). Concerning the process model, patient flow can be divided in three stages: inflow, throughput and outflow. For the simulation model to be a good reflection of reality, all three stages have to be included at a desirable level of detail (Asplin et al. 2003, Saghafian et al. 2015).

3. DATA QUALITY PROBLEMS

An overview of the attributes included in the dataset under study is provided in Table 1. Within this dataset, several data quality problems can be distinguished. Firstly, certain attribute values are not recorded for all

patients. Timestamps of the first consultation by a physician, the first time a patient is assigned to a box in the ED and the time a patient is medically finished (i.e. approved by a physician to leave the ED) are some examples. Another attribute that is missing for some patiens, is the triage code and a timestamp of the triage process. The triage code indicates the severity of a patient's symptoms. The triage process is only executed between 7 a.m. and 10 p.m., so most missing values are due to the fact that patients arriving during the night shift were not subjected to the triage process. The missing attribute value is not really a quality problem, but the triage code is a necessary input value to the simulation model because patient streams and service times are determined according to triage code.

Secondly, some patient records contain implausible attribute values. First, timestamps may not follow the logical order of patient flow throughout the ED. Consider a patient for which the timestamp of the first consultation with a physician falls before the timestamp of triage or a patient which is only medically finished after leaving the ED. Second, mutually dependent activities take place separately sometimes. An example of this quality issue is the fact that a radiological or laboratory examination request is ordered, but the examination never started and no results are received. Also, a mutation request (i.e. admission request to an inpatient unit) and plan do not always precede an admission to an inpatient unit. Third, attribute values can be incorrect or imprecise without being incoherent with other attribute values. Medical staff sometimes bundles administrative tasks for a group of patients, so timestamps do not always reflect the exact time of an activity. Typing mistakes are another common source of incorrect values.

Finally, particular attributes can be absent in the data file. If a fundamental input variable for the simulation model is missing, the quality of the results is doubtful. Sometimes the values of these attributes can be derived from other, known, attributes, but these tend to be approximations which build upon particular assumptions. Some missing attributes in the data file of the hospital under study are the end times of activities, which are needed to calculate service durations. Other examples include the resources carrying out an activity and the different types of radiological examinations that a patient has undergone.

The aforementioned problems are some examples of quality problems that might be present in the EHRs of an ED. There are several reasons underlying these problems. The ones most commonly indicated by medical and administrative staff are described below. First of all, medical staff has other priorities and can forget to register actions at busy moments. They also indicated that rules exist with reference to patient flow. However, those rules are not always complied with. Context, situation, experience and gut feeling play a role in the decision making process in an ED. For example, a child that is very upset and has the same triage code as an adult, but a later arrival time, can be treated earlier. Another potential reason of data quality problems, is the fact that some units within the ED work independently. These units are radiology, psychiatry, paediatrics and the laboratory. They have their own resources, EHR system and practices. Integrating data of all units within the ED can create inconsistencies. Furthermore, records of patients leaving the ED to the operating room or intensive care unit may contain quality problems because the primary focus is on saving the patient's life. A last source of data quality problems that is commonly indicated by hospital staff are registration errors (e.g. typing mistakes), since a lot of information is recorded manually.

Table 1: Overview of Attributes in the Data File under Study

ATTRIBUTE	EXPLANATION
TIMESTAMPS (Date + time)	
Start date (only date)	The date a patient arrives at the ED and is first registered in the system
T Arrival	Timestamp expressing patient registration in the system
T First triage	Timestamp representing the completion of triage (the point at which a triage code is entered in the system)
T First physician	Timestamp at which the doctor starts writing a report after a first consultation with the patient
T First physical location other than waiting room	Timestamp when the patient was moved out of the waiting room to another physical location (box) for the first time
T Start observation	Timestamp at which the doctor decides that the patient needs to be placed in observation
T Medically finished	Timestamp at which the doctor "signs off" the patient (all medical actions are completed from the perspective of the ED)
T Mutation request	Timestamp when a bed in the hospital was requested for the patient
T Mutation plan	Timestamp when a bed in the hospital is assigned to the patient
T Departure	Timestamp when patient left the ED
T Rx request	Timestamp of the first request for a radiological examination (entered by the physician)
T Rx start execution	Timestamp when the radiological examinations are executed
T Rx first report	Timestamp of the first finished report of the radiological examinations
T Rx last report	Timestamp of the last finished report of the radiological examinations
T Lab request	Timestamp of the first request for a lab test (blood, urine, …)
T Lab first sample received	Timestamp when the first sample is taken for a lab test
T Lab first report	Timestamp when the first finished report was written of the lab results
T Lab last report	Timestamp when the last finished report was written of the lab results
T Pharmacy first use	Timestamp when something was taken from the electronic medicine cabinet (eg. medication, band aid, ...)
T Last triage	Timestamp when the final triage code was given
NUMERICAL	
Patient number	Unique number assigned to every patient, used for identification purposes
File number	Unique number for every file available for a patient e.g. every time a patient visits the hospital, a new file is opened
Age	The age of the patient
Discharged outside the hospital	Dummy variable indicating if a patient is discharged to a place outside the hospital e.g. home, other hospital, nursing home…
CATEGORICAL	
First triage code	The first triage code assigned to a patient (ESI-triage, code between 1-5)
Last triage code	The last triage code assigned to a patient
Mutation unit	The inpatient unit an admitted patient is assigned to
Brought by	Indicates if a patient came to the hospital by ambulance, police, walk-in, transfer or internal transport
Destination after ED	Indicates the destination of the patient after the ED, for example home, inpatient unit, nursing home, other hospital, passed away…
Discharge type	A patient can be discharged on medical advice, admitted, LWBS, left against medical advice or passed away.
FREE TEXT	
Main complaint	Most important symptoms of a patient when arriving in the ED
Diagnosis	The final diagnosis made by a physician, registered at the time of departure. This should be a categorical attribute, but the ICD-9 coding is not consistently followed.

4. DATA QUALITY FRAMEWORK

The previous section outlined potential data quality problems. In order to identify such problems, thorough quality investigation of the data recorded in EDs is required. This matter receives limited attention in literature on ED simulation. Consequently, there is a need for a structured approach for evaluating the quality of data from EHRs. In this section, a categorisation of the

problems occurring in the EHRs of an ED is developed, based on existing data quality literature.

4.1. Literature review

In the literature, several general taxonomies for data quality problems have been provided. Table 2 gives an overview of these frameworks and the main classification basis used to categorise data quality problems. Data quality problems can be classified according to granularity level, schema or instance level, problem manifestation and fitness for use.

Table 2: Overview of Existing Data Quality Frameworks and the Main Classification used.

	MAIN CLASSIFICATION			
FRAMEWORK	Granularity level	Schema or instance level	Problem manifestation	Fit for use model
Wang and Strong (1996)				x
Rahm and Do (2000)	x	x		
Kim et al. (2003)			x	
Mueller and Freytag (2003)			x	
Barateiro and Galhardas (2005)	x	x		
Oliveira et al. (2005)	x			
Gschwandtner et al. (2012)	x			
Kahn et al. (2012)				x
Weiskopf and Weng (2012)				x
Mans et al. (2015)			x	

One of the first frameworks was proposed by Wang and Strong (1996). This framework is based on quality aspects that are important to data consumers. It is built around the concept of fitness for use, which emphasises the importance of taking the viewpoint of the end user into account. The framework consists of four dimensions: intrinsic, contextual, representational and accessibility data quality. The first dimension comprises quality problems that are inherent to the data. The second dimension captures the fit for use concept. Data can be accurate, but not of good quality for the application. The last two dimensions are related to the system used for data gathering.

Rahm and Do (2000) created a data quality framework based on two distinctions: (i) single-source vs. multi-source problems and (ii) schema level vs. instance level problems. Single-source problems are concerned with only one dataset and multi-source problems with the integration of multiple datasets. Schema level problems contain data quality issues emerging because of a poor data model design and a lack of enforcement of data entry rules. Instance level problems are data quality problems inherent to the data values. This category is comparable with the intrinsic data quality category of Wang and Strong (1996). The categories of data quality defined by Barateiro and Galhardas (2005) are based on the same distinctions as Rahm and Do (2000). Oliveira et al. (2005) distinguishes four granularity levels based on the different relations apparent in a relational database. This division is comparable with the single- and multiple-source classification, the only difference is that Oliveira et al. (2005) focus on the number of datasets to integrate. Gschwandtner et al. (2012) classify time-oriented data quality problems into single- and multiple source problems.

In other frameworks, the main categorisation is based on the possible data anomalies instead of the granularity level of the data. Mueller and Freytag (2003) divide data quality problems into syntactical anomalies, semantic anomalies and coverage anomalies. All categories are applicable at different levels in a database, from a single dataset to a complete relational database. Kim et al. (2003) developed a comprehensive classification of dirty data based on the manifestation of the quality problem. The main subdivision is between missing and not-missing data. Not-missing data is broken down further into wrong data and not wrong, but unusable data. In all categories, problems present in a single- and multi-source dataset and at the system and instance level can be found.

The main classifier differs between the existing frameworks, but most frameworks overlap in the final data problems identified. In some frameworks these final problems are very specific, so that they can be measured by specific tests (e.g. Barateiro and Galhardas (2005), Gschwandtner et al. (2012), Kim et al. (2003), Oliveira et al. (2005), Rahm and Do (2000)). Examples of those final problem types are missing values, spelling errors, duplicated records, values outside domain ranges etc. Other frameworks define non-overlapping, but broad problem categories, like accuracy, completeness, believability, timeliness, etc. (e.g. Wang and Strong (1996)).

The previous frameworks are general data quality frameworks, applicable and adjustable to nearly every research context. Focusing on data quality in healthcare, three frameworks have recently been developed. These are indicated in grey in Table 2. Mans et al. (2015) define four classes of problem types: missing data, incorrect data, imprecise data and irrelevant data. These problem classes are identified based on event logs from EHRs. An event log is an ordered list of events. An event represents "something" that happens within a process and is related to a case such as a patient. Consider, for instance, the start of an examination for a particular patient. Additional information that can be recorded about the event includes its timestamp and the resource that is associated to the event (Mans et al. 2015). Within the ED context, event logs can convey insights in, for instance, the order in which a patient undergoes activities, the resource executing these activities and, potentially, even on the patient's condition. This information can be highly relevant for simulation purposes. Kahn et al. (2012) and Weiskopf and Weng (2012) classify EHR data quality problems based on the framework of Wang and Strong (1996). The framework is adjusted to only incorporate data quality problems relevant in a healthcare context and especially in the reuse of data for clinical research. As a result, only intrinsic and contextual data quality problems are taken into account.

Since the approach used in the development of data quality frameworks for EHRs focuses on the reuse of data in clinical research, there are still deficiencies with

regard to the use in operations research contexts in general and simulation in particular. Also, the level of detail in the data quality dimensions is insufficient. The categories are too general, with every category still containing a lot of distinct problems. To be able to define quality assessment methods and to avoid overlooking problems that are not immediately recognisable, a greater level of detail is necessary.

4.2. Data quality framework

All discussed frameworks contain particular data quality problems that are present in the dataset of the ED under study, but none of them completely covers all the identified data quality problems. Since insights from the existing frameworks – both general and healthcare specific – are valuable, these form the basis for establishing a new data quality framework.

The objective of this paper is to build a framework to identify data quality problems in an extracted data file of an ED intended for use in an operations research context, especially simulation. We assume the hospital is the only authorised user of the database, so they compose a data file with the requested information. This file is made available to the researcher. This means that a classification based on granularity level is superfluous. Also, since we are not concerned with the design of the data gathering system, only instance level problems are identified. The two remaining classifications, a distinction based on problem manifestation and fit for use models, are both applicable. Since the context is already defined, we decide to use a problem manifestation classification. The framework is developed with a focus on one application domain, but this does not preclude the use in other research contexts such as other operations research studies in healthcare.

The established framework can be found in Figure 1. The main classification used in the framework is based on the framework of Kim et al. (2003), because this fits the extracted data file better than the classification of Mueller and Freytag (2003). The problem classes of Mans et al. (2015) are also covered in the framework. Data quality problems are split into missing data and not-missing data. The latter category is further divided into wrong data and not wrong but not directly usable data. The name of the last subcategory is changed compared to the framework of Kim et al. (2003), where this category is named not wrong but unusable. With regard to the intended use, the new name covers the category's content better. It contains data that is not wrong, but further data processing is required to make it usable for the purpose at hand. A general example is the presence of start- and end timestamps of an activity, while activity durations are needed.

The main classification is further divided until specific data quality problems are identified. This makes it possible to define measures to assess the extent of the data quality problem for every end category of the framework. End categories consists of only one problem type and there is no overlap between them. However, it is possible that a specific problem in a dataset can be classified in multiple categories. Especially if the data quality assessment techniques of more than one category lend themselves to detect the problem. The different categories of the framework are described in sections 4.2.1 to 4.2.3. The numbers between brackets in Figure 1 are used to refer to the structure of the framework.

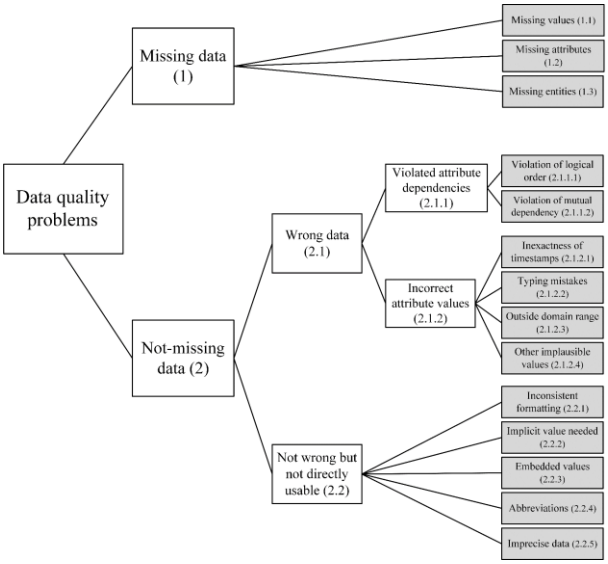

Figure 1: Data Quality Framework for EHRs of EDs in operations research context

4.2.1. Missing data

Missing data (1) is data that is missing in a field while it should not be missing (Kim et al. 2003). Missing data are a very common and inevitable problem (Penny and Atkinson 2001). The fact that some data values are missing can have two important negative effects. First, it can lead to biased estimates for statistics such as central tendency, dispersion or correlation. In a simulation context, biased input parameters can result from missing data. The extent of the negative effect depends on the cause of missing data, i.e. whether missingness is caused by other factors. In case it is related to the (unknown) value of the attribute itself or another attribute in the dataset, it can result in a distortion of the estimates. In case the missing values are randomly distributed in the dataset, the bias is minimal. Secondly, missing data reduce the statistical power of the analysis, because there are less cases available for the analysis (Tsikriktsis 2005). Because missing data can have an impact on the credibility of the simulation study, this is the first category of data quality problems in our framework.

There are three types of missing data: values, attributes and entities. Missing values (1.1) are mandatory attribute values that are missing for certain patients. For example, the triage code is missing for a patient, while triage is executed for every patient arriving at daytime. Other examples are timestamps of performed activities and the discharge type of a patient.

Missing attributes (1.2) are attributes needed as input to the simulation study that are not recorded in the data file. The difference with the previous category is that the values of these attributes are missing for every patient in

ISBN 978-88-97999-89-8; Bruzzone, Frascio, Longo and Novak Eds.

the dataset. Sometimes the attributes are recorded in the EHRs but not included in the extracted data file. Another possibility is that the attributes are not recorded at all. It is possible that timestamps of certain activities are missing or that it is unknown which radiological examinations patients have undergone or which resource executed a task.
The last type of missing data are missing entities (1.3). Normally, every arriving patient and every action executed on that patient has to be registered. However, the dataset at hand showed periods in which no patients arrived for extended periods of time. This is not realistic, so there are patients missing in the data file. A possible reason is a technical failure of the system or an error in the data extraction process.

4.2.2. Wrong data

Wrong data (2.1) is the first of two not-missing data categories. Quality problems manifesting themselves as wrong data are grouped into violated attribute dependencies and incorrect attribute values.
Violated attribute dependencies (2.1.1) are data values that cannot be identified as wrong without information about other attribute values. The violation of logical order category (2.1.1.1) describes problems with the timestamps of successive activities. For example, a patient can only be triaged after arrival, radiological examinations are executed after a first consultation by a physician and no actions can happen to the patient after he left the ED.
The second type of problem related to attribute dependencies is a violation of mutual dependency (2.1.1.2). Attributes are mutually dependent if the value of one attribute affects the value of another attribute. An example is the fact that a patient who has been admitted to the hospital, needs to have a mutation request and mutation plan timestamp and an internal unit assigned to him. Other examples are that if a patient has never seen a physician, his discharge type has to be set at 'left without being seen' and that a patient aged under 16 will be seen by a paediatrician.
Incorrect attribute values (2.1.2) are data values that are wrong on their own, without violating their relation with other attributes. This category contains four problem types: inexactness of timestamps, typing mistakes, values outside domain ranges and other implausible values. The first problem type (2.1.2.1) indicates the fact that timestamps may be recorded imprecisely. Physicians giving low priority to administrative tasks, sometimes results in bundling these tasks for several patients. The timestamps are an inaccurate representation of the activity time because the registration is done afterwards. Also, timestamps can be wrong because of input mistakes if they are not acquired automatically at the time a doctor changes a medical file.
The second problem type are typing mistakes (2.1.2.2), e.g. a typing mistake in the diagnosis field. The focus in this category is on text fields, because typing mistakes in numerical or categorical fields may be identified in one of the other subcategories of the incorrect attribute values class, or they may be unidentifiable (e.g. triage code 3 instead of 4 is registered). Also, typing mistakes are very clear in text fields because it leads to inexistent words, but in numerical fields they are more difficult to identify. In numerical or timestamp fields, typing mistakes manifest themselves as values outside the domain range or implausible/inexact values. Assigning these errors to typing mistakes is difficult, so we do not consider them in this category.
Values outside the domain range (2.1.2.3) are the third problem type. This category includes timestamps, numerical and categorical values that are impossible given the domain ranges. A timestamp has to lie between the start and end of the data extraction period, triage codes have to be values between 1 and 5 and there are five possible discharge types for a patient, namely discharged home, admitted to the hospital, left against medical advice, left without being seen and passed away.
The last problem type is a residual category for wrong data values that do not fit in one of the previous ones (2.1.2.4). For example, resource information can be wrong if a resource forgets to log out from the system, so every action on a computer is registered as done by the same resource. This makes it seem like an implausible number of actions are executed by one resource within a certain time period.

4.2.3. Not wrong but not directly usable data

The second not-missing data quality category (2.2) is different from the previous one in that the data values are not wrong. However, the raw data is not suitable for the specific task at hand. After some data processing efforts, the values can still be used in the analysis. This category contains five specific problem types: inconsistent formatting, implicit value needed, embedded values, abbreviations and imprecise data. Inconsistent formatting (2.2.1) means that there is an inconsistency in the coding of the values within one attribute or among attributes. There are several possibilities: the same representation can be used for different values (e.g. an empty field indicates either a zero or a missing value), different representations for the same value (e.g. a zero is indicated by 0 or an empty field) and a different format for the same value types (e.g. the diagnosis is coded with ICD-9 or free text, dates are presented as DD-MM-YY or YY-MM-DD).
Implicit value needed (2.2.2) means that there is no value present for a patient because an action is not executed or not all details of the action are registered in the data file. Since the attribute is inherent to each patient or activity, this value can be assigned without executing the process or registrating all activity details. If the value is needed in the simulation study, this is perceived as a quality problem. The fact that triage is not executed at night, while patient flow through the ED depends on triage code, fits in this category. Even though patients arriving at night have a particular severity of their condition and, hence, an implicit triage code, no explicit value will be assigned. The presence of start- and end times of an activity, while the duration is needed, can also be

categorised as implicit value needed. The value is implicitly present in the data file, but not recorded as a separate attribute.
Embedded values (2.2.3) are the third problem type, indicating data fields containing more than one value. For example, a timestamp field may contain date and time information, while only time information is needed to create an arrival distribution depending on the hour of the day.
Abbreviations (2.2.4), the fourth problem type, are also correct values, but their meaning has to be derived to be useful. Finally, the imprecise data category (2.2.5) comprises values that are correct but do not contain the necessary amount of detail. For example, it is indicated that radiological examinations are executed but not which specific examinations. Another problem fitting in this category are timestamps with only a date of execution, not the exact time.

5. DATA QUALITY ASSESSMENT

The data quality framework gives an overview of possible quality issues in an ED dataset. Data quality assessment techniques can be used to check the presence of a certain problem type. Also, the severity of the quality problem can be quantified for a number of problem types. To this end, possible techniques for identifying and measuring data quality problems are provided for the end categories present in the framework. These categories are indicated in grey in figure 1.

5.1. Missing data

5.1.1. Missing values

The presence and quantity of missing values seems straightforward to identify, but an important consideration has to be made. In case null values are not possible for an attribute, every empty, n.a. or zero field indicates a missing value. So for mandatory attributes, the number of missing values is easily determined by counting the number of missing values. If missing values are not consistently represented, all representations have to be defined before counting. Since absolute values have no meaning without a reference value, the percentage of missing values for a specific attribute i can be calculated as follows:

$$\frac{Total\ number\ of\ missing\ values\ for\ attribute_i}{Total\ number\ of\ records\ in\ data\ file} * 100\% \quad (1)$$

In the other case, if null values are possible for an attribute, a distinction has to be made between missing and null values. A possible way to do this is by identifying dependencies with other attributes. For example, if a patient's discharge type is 'left without being seen', the timestamp of the first consultation with a physician is not recorded. In all other cases, this timestamp has to be present. Another example is that a mutation plan and mutation request are not assigned for a patient who is discharged home, otherwise this value is missing. By identifying certain dependencies between the attribute under study and other attributes in the data file, missing values can be identified. After that, the number of missing values can be counted and the extent of the problem can be determined by formula (1).
An important consequence of missing values is the existence of incomplete records. A lot of incomplete records undermine the possibility to reconstruct the exact patient flow through the ED. So besides assessing the missingness for every attribute separately, the amount of complete patient records is also an important measure. Since missing values do not necessarily occur within the same patient records for different attributes, the amount of incomplete patient records is not just the maximum of formula (1) over all attributes. Instead, in the most extreme case, it can be the sum of formula (1) over all attributes. To calculate the amount of incomplete records, every patient record has to be checked for missing values in one of the attributes. The percentage of incomplete records is defined with formula (2):

$$\frac{Total\ number\ of\ incomplete\ records}{Total\ number\ of\ records\ in\ data\ file} * 100\% \quad (2)$$

5.1.2. Missing attributes

Missing values are relatively easy to identify and quantify in comparison with missing attributes and entities. Regarding missing attributes, the number of missing attributes depends on the application. In case of simulation, the necessary attributes depend on the specific part of the ED to model and on the amount of detail taken into account. If attributes are missing, the severity of this quality problem is contingent on the derivability of the attribute values from other data or the possibility to deduce a good estimate based on on-field observations or surveys. Given these considerations, it is possible to assess the presence of this quality problem, but measuring the extent of the problem is a subjective evaluation by the user of the data given the specific application.

5.1.3. Missing entities

Concerning missing entities, it is also difficult to quantify the problem. Since missing entities are not registered, the number of missing entities is not deductible from the data file. However, it is possible to determine if the quality problem is present, since it is characterised by extended time periods without arrivals. Those time periods are longer than the normal interarrival times. The maximum possible interarrival time is based on judgment by ED personnel.

5.2. Wrong data

5.2.1. Violation of logical order

Violation of logical order implies that the patient flow based on timestamps in the data file is not correct compared to the normal patient flow. Since patient flow is site- and context-specific, the first step is to define the order of the n events in the regular patient flow:

$$T\ event_1 < T\ event_2 < \cdots < T\ event_n \quad (3)$$

Note that some activities can take place in parallel or random order, so these activities have to be excluded from the order of events (e.g. different examinations).
Only timestamps of sequential activities have to be checked, since this automatically implies that all other dependencies are satisfied:

$$T\ event_i < T\ event_{i+1} \quad \forall i < n \tag{4}$$

The extent of the quality problem can be measured by calculating the number of records for which the logical flow of events is violated and dividing it by the total number of records.

$$\frac{Number\ of\ records\ with\ T\ event_i > T\ event_{i+1}}{Total\ number\ of\ records\ (excl.\ missing\ T)} * 100\% \quad \forall i < n \tag{5}$$

The records with missing values for one or more timestamps are excluded from the denominator, since it is impossible to define the patient flow of those patients based on incomplete records. If patient flow depends on patient characteristics, caution should be exercised, since there is more than one possible ordering of events. When violation is suspected based on the regular patient flow, but the recorded patient flow seems possible given patient characteristics, expert confirmation is advisable.

5.2.2. Violation of mutual dependency

Mutual dependency means that the value of one attribute has an impact on the value of another attribute. For example, a patient with an age below 16 has to be assigned to paediatrics. If this dependency is violated, it indicates an error in one of the attribute values. To assess the data quality for this problem type, the number of records for which a specific mutual dependency is broken, has to be calculated. This number is divided by the total number of records in the data file. Records with missing values for the attributes under study are not excluded, since the presence of a value for one attribute can imply that the other attribute also has to be present or vice versa. Therefore, the fact that a value is present or missing can also imply a violation of mutual dependency.

$$\frac{Number\ of\ records\ with\ attribute_i \nsim attribute_j}{Total\ number\ of\ records\ in\ data\ file} * 100\% \tag{6}$$

An important note with this formula is that only attribute couples (i,j) with a mutual dependency between attributes i and j are tested on this quality issue.

5.2.3. Inexactness of timestamps

This category contains timestamps that are possible and hence do not violate any dependency with other attributes, but they are not realistic. By calculating KPI's or durations, outliers can be identified. These outliers can indicate incorrect timestamps for the attributes used in the calculations. Examples are length of stay (T departure – T arrival), door to doctor time (T first physician – T arrival) or durations between successive events. The percentage of inexact timestamps can be calculated by formula (7):

$$\frac{Total\ number\ of\ outliers}{Total\ number\ of\ records\ (excl.missing)} * 100\% \tag{7}$$

The denominator does not contain records with missing values for one of the attributes used as input to the calculations. An outlier can be identified as a record for which the absolute standardised value is larger than 4 (see Hair et al. 2009 for more information). Given the unpredictable and complex nature of an ED, it is difficult to identify which derived values can be seen as outliers. Even though outlier analysis can be used to identify possible quality problems, the measures have to be interpreted carefully. Resource information can also be an indication of inexact timestamps. If the number of activities executed by one resource at more or less the same time is unrealistic, there is a high probability that the resource bundled the administrative tasks for several patients.

5.2.4. Typing mistake

The focus of this quality issue is on text fields with typing mistakes. This means that a typing mistake can be identified as an unknown word by using a list of possible words given the attribute (e.g. diagnosis) or a dictionary. Since this is very complex, quality assessment for this problem type will not be discussed further.

5.2.5. Outside domain range

Numerical attributes (or timestamps) with a value smaller than the minimum or larger than the maximum acceptable value lie outside the domain range. Correct attribute values meet the following equation:

$$Min_{Ai} \leq Value_{\ Ai} \leq Max_{Ai} \tag{8}$$

The subscript Ai stands for attribute i. For categorical attributes, this quality problems exists if the assigned value is no element of the possible value set. Normally,

$$Value_{Ai} \in \{value\ set\} \tag{9}$$

To assess the quality for this problem type, formula (10) can be used.

$$\frac{Number\ of\ values\ outside\ domain\ range\ attribute_i}{Total\ number\ of\ records\ (excl.missing)} * 100\% \tag{10}$$

In this equation, the denominator contains all entities with a value recorded for the attribute under study. Missing values are excluded since we cannot check the domain ranges.

5.2.6. Other implausible values

Since this is the rest category, it is not possible to define a general assessment method for these problems. If there is a suspicion of a quality problem not captured in the previous categories, this can be checked and a percentage of implausible values can be calculated. An example is calculating the number of actions executed by one resource within a given time period. If this amount is not realistic, it is an indication of incorrect resource

information. Another indication are resources executing tasks outside their shift times. Note that this is not the same as the bundling of administrative tasks, which is already covered in the inexactness of timestamps category.

5.3. Not wrong but not directly usable

For not wrong but not directly usable data, approaches to identify the presence of the problem types are defined. Moreover, solution methods to convert the data to values usable in the application are proposed. The ease of transformation is important to estimate the impact of the data quality problem. As this category does not contain unsolvable problems, quantifying the problem is not of great value

5.3.1. Inconsistent formatting

By inspecting data values of the same type within and among attributes, differences in coding can be identified. If the problem of inconsistent formatting is present, the values of the attributes have to be reformed for a consistent representation. For standard data formats (e.g. dates, times, names…), this can be easily done by changing the cell properties with a data analysis or spreadsheet program (e.g. Microsoft Excel, R). In case of application domain specific coding, like ICD-9 codes in a healthcare context, reformatting is more complex. A possible solution is to look for the ICD-9 code most closely related to the description of the diagnosis. The free text value can be replaced with the associated code.

5.3.2. Implicit value needed

As indicated in the discussion of the data quality framework, missing values have to be separated from null values. Null values occur when an activity has not been executed for a patient. Sometimes, the attribute value is inherent to the patient, so a value can be assigned without executing the activity. If the attribute is a necessary input to the simulation model, the implicit values have to be determined. Consider null values for triage code during the night shift as an example. There are several ways to define the triage code afterwards. Based on the symptoms and diagnosis in the data file, an expert can be asked to define the triage codes for patients arriving at night. Also, observations at night can give an indication of the distribution of patients according to triage code. Another possibility is to estimate the distribution at night based on the daytime distribution if they are similar. The distribution of diagnoses (ICD-9 codes) can also be used as an approximation of the triage code distribution.

This category also contains activity information that is not recorded. The attribute is not missing since the value is included implicitly in other attribute values. An example are service times, which can be derived from start- and end timestamps of an activity. By calculating the difference between the start and end of the activity, the service times can be deducted.

5.3.3. Embedded values

Attributes with problematic embedded values can be identified by first indicating the values needed as input to the simulation model. If these values are present in combination with another value within one field, the attribute value has to be split in different values to be useful. Embedded timestamps are attributes containing date and time, while only the time is valuable. In Excel, time information can be obtained by subtracting the date from the attribute value. In other data editor software, like R, it is possible to split the attribute value according to a prespecified rule.

5.3.4. Abbreviations

Abbreviations can be present in a free text field. An abbreviation is easy to recognise, but detecting attributes containing abbreviations is time-consuming. The most straightforward way to do this is by just going through the data file and checking the attribute values. Standard abbreviations can be simply transformed to complete words, but for domain-specific terminology, expert assistance is desirable.

5.3.5. Imprecise data

The last problem type, imprecise data, is relatively easy to identify, but hard to solve. Measuring units of an attribute value are an indication of precision and they are clear from the data file. If the attribute values do not contain enough detail for the target use, extra data can be extracted if recorded. For example, radiological examinations are only indicated by a date, but timestamps are available in the database of the radiological unit. This information can be requested. Otherwise, empirical data gathering or modelling on a higher abstraction level are possible solutions.

6. CONCLUSIONS AND FUTURE RESEARCH

In this paper, data quality problems and assessment techniques are developed from the viewpoint of simulation in EDs. The reliability of a simulation model developed to analyse ED performance, depends on the input data used. Therefore, the quality of the data used as input to the simulation model has to be investigated. Data acquisition, data quality assessment and data quality improvement are three necessary steps preceding the construction of a simulation model. The focus of this paper is on quality assessment of the EHRs in an ED. Data quality assessment is preceded by the identification of potential data quality problems. The focus is on problems with a possible impact on simulation, so data quality problems related to the input data of the model. Based on an extracted data file from the ED of a Belgian university hospital, a data quality problem framework is proposed. The framework builds upon insights from previous research, with the main classification of Kim et al. (2003) as starting point. Quality problems are divided in missing data and not-missing data problems. Not-missing data has two subcategories: wrong data and not wrong but unusable data. This main classification is further divided until specific data quality problems are

identified. A total of fourteen specific, non-overlapping problem types are found. For each problem type, identification methods are presented together with formulas for quantifying the extent of the quality problem if relevant.

The purpose of this paper was to clarify the problem and importance of data quality in operations research. Not only survey data, but also electronically recorded data can contain errors and should be checked systematically and used carefully. The framework in combination with the assessment methods provide guidance to researchers for inspecting input data before use. As a next step, a tool for data quality assessment will be developed building upon the conceptual foundations outlined in this paper. This tool will require certain context-specific inputs by the researcher, such as the logical flow of events to test violation of logical order. This information will be used to test data files on several quality aspects and to indicate problem areas in the dataset.

There are several possibilities for future research. A possible topic is the extension of the framework to other operations research techniques and to operations research in other healthcare domains. Also, the framework can be tested and eventually modified for use in other countries to enhance the generalisability. Another interesting field to investigate more thoroughly, is the development of quality assessment techniques for the different data quality problems identified in the framework. Some basic techniques are provided in this paper, but there may be more advanced possibilities. Finally, investigating improvement techniques for the different data quality problems is a valuable direction for future work.

REFERENCES

Ahmed M.A., Alkhamis T.M., 2009. Simulation-optimization for an emergency department healthcare unit in Kuwait. European Journal of Operational Research, 198, 936-942.

Asplin B.R., Magid D.J., Rhodes K.V., Solberg L.I., Lurie N., Camargo C.A., 2003. A conceptual model of emergency department crowding. Annals of Emergency Medicine, 42(2), 173-180.

Barateiro J., Galhardas H., 2005. A survey of data quality tools. Datenbank-Spektrum, 14, 15-21.

Bergs J., Vandijck D., Hoogmartens O., Heerinckx P., Van Sassenbroeck D., Depaire B., Marneffe W., Verelst S., 2016. Emergency department crowding: Time to shift the paradigm from predicting and controlling to analysing and managing. International Emergency Nursing, 24, 74-77.

Carmen R., Van Nieuwenhuyse I., 2014. Improving patient flow in emergency departments with OR techniques : a literature overview. FEB Research Report KBI_1425, KU Leuven, Belgium.

Gschwandtner T., Gärtner J., Aigner W., Miksch S., 2012. A taxonomy of dirty time-oriented data. International Conference on Availability, Reliability, and Security, 58-72.

Gul M., Guneri A.F., 2015. A comprehensive review of emergency department simulation applications for normal and disaster conditions. Computers & Industrial Engineering, 83, 327-344.

Guo H., Goldsman D., Tsui K., Zhou Y., Wong S., 2016. Using simulation and optimisation to characterise durations of emergency department service times with incomplete data. International Journal of Production Research, 54(21), 6494-6511.

Hair J.F.J., Black W.C., Babin B.J., Anderson R.E., 2009. Cleaning and transforming data. In: Hair J.F.J., Black W.C., Babin B.J., Anderson R.E., 7th ed. Multivariate Data Analysis: a global perspective. Pearson, 33-90.

Kahn M.G., Raebel M.A., Glanz J.M., Riedlinger K., Steiner J.F., 2012. A pragmatic framework for single-site and multisite data quality assessment in electronic health record-based clinical research. Medical care, 50(7), 21-29.

Kim W., Choi B.J., Hong E.K., Kim S.K., Lee D., 2003. A taxonomy of dirty data. Data Mining and Knowledge Discovery, 7, 81-99.

Mans R.S., van der Aalst W.M.P., Vanwersch R.J.B., 2015. Process Mining in Healthcare: Evaluating and Exploiting Operational Healthcare Processes. Switzerland:Springer.

Oh C., Novotny A.M., Carter P.L., Ready R.K., Campbell D.D., Leckie M.C., 2016. Use of a simulation-based decision support tool to improve emergency department throughput. Operations Research for Health Care, 9, 29-39.

Oliveira P., Rodrigues F., Henriques P.R., 2005. A Formal Definition of Data Quality Problems. Proceedings of the International Conference on Information Quality.

Penny K.I., Atkinson I., 2012. Approaches for dealing with missing data in health care studies. Journal of Clinical Nursing, 21, 2722-2729.

Pipino L.L., Lee Y.W., Wang R.Y., 2002. Data quality assessment. Communications of the ACM, 45(4), 211-218.

Rahm E., Do H.H., 2000. Data cleaning: problems and current approaches. Bulletin of the IEEE Computer Society Technical Committee on Data Engineering.

Saghafian S., Austin G., Traub S.J., 2015. Operations research/management contributions to emergency department patient flow optimization : review and research prospects. IIE Transactions on Healthcare Systems Engineering 5(2), 101-123.

Tsikriktsis N., 2005. A review of techniques for treating missing data in OM survey research. Journal of Operations Management, 24, 53-62.

Wang R.Y., Strong D.M., 1996. Beyond Accuracy: What Data Quality Means to Data Consumers. Journal of Management Information Systems, 12(4), 5-33.

Weiskopf N.G., Weng C., 2013. Methods and dimensions of electronic health record data quality assessment: enabling reuse for clinical research. Journal of the American Medical Informatics Association, 20(1), 144-151.

CLOSED-LOOP VERIFICATION APPROACH FOR THE IDENTIFICATION OF MOTION-BASED ACTION POTENTIALS IN NEURAL BUNDLES USING A CONTINUOUS SYMBIOTIC SYSTEM

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ABSTRACT

The identification and the corresponding verification of motion- and sensory feedback-based action potentials in peripheral nerves are prerequisites for applications like prosthesis control or limb stimulation in medical technology. After a description of a prototype of a biosignal acquisition and identification system we introduce the symbiotic cycle, based on the well-known term symbiotic simulation (Aydt, Turner, Cai, and Low 2008), (Aydt, Turner, Cai, and Low 2009). As an example we present a data driven method to create a human readable model without using presampled data. This method consists of symbiotic continuous system combining a physical system, a simulation system and an agent based machine learning system. All components in the system interact in a symbiotic way. The result of each component is used as an input by the others and vice versa. Finally bootstrapping as a direct consequence of the symbiotic interaction is trivial for all components. The closed-loop identification method is integrated into this symbiotic cycle. This verification approach is the main focus of the paper.

Keywords: symbiotic simulation, symbiotic cycle, system identification, agent-based evolutionary computation

1. INTRODUCTION

The identification of motion- and sensory feedback-based action potentials in peripheral nerves is a great challenge in medical technology. It is the prerequisite for applications like prosthesis control or limb stimulation. Based on the acquisition of action potentials, the identification process correlates physiological and motion-based parameters to match movement trajectories and the corresponding action potentials. The identification method is based on the continuous mode symbiotic cycle, combining a physical system, a simulation system and an agent based machine learning system. As an example a data driven method to create a human readable model without using presampled data is presented. All components in the system interact in a symbiotic way. The result of each component is used as an input by the others and vice versa. At first the prototype of a smart modular biosignal acquisition and identification system is presented, acting as the physical target system in the symbiotic cycle, presented subsequently. In this paper the focus is on the identification method based on a data driven approach and its verification. We present the closed-loop identification method, implemented using a symbiotic continuous system (Aydt, Turner, Cai, and Low 2008), (Aydt, Turner, Cai, and Low 2009), consisting of a robotic based trajectory generation, the nerve simulation and an agent-based machine learning system. We introduce the model generation process and show the closed-loop verification approach of the identification method.

1.1. The Prototype of a Smart Modular Biosignal Acquisition and Identification System

The key challenge is the human machine interface of prosthesis and its movement control. The objective is to use biosignals for the information transfer between human being and prosthesis. So an interface is needed to interfere between the command-level and the actuator- and sensor- level. The approach discussed in this paper is based on the direct use of the action potentials of peripheral neural bundles via an electroneurogram (ENG) (Gold, Henze, and Koch 2007), (Neymotin, Lytton, Olypher, and Fenton 2011). So, the employment of invasive intra-neural sensors (Micera, Carpaneto, and Raspopovic 2010), (Micera, Citi, Rigosa, Carpaneto, Raspopovic, Pino, Rossini, Yoshida, Denaro, Dario, and Rossini 2010), (Raspopovic, Capogrosso, Petrini, Bonizzato, Rigosa, Di Pino, Carpaneto, Controzzi, Boretius, Fernandez, Granata, Oddo, Citi, Ciancio, Cipriani, Carrozza, Jensen, Guglielmelli, Stieglitz,

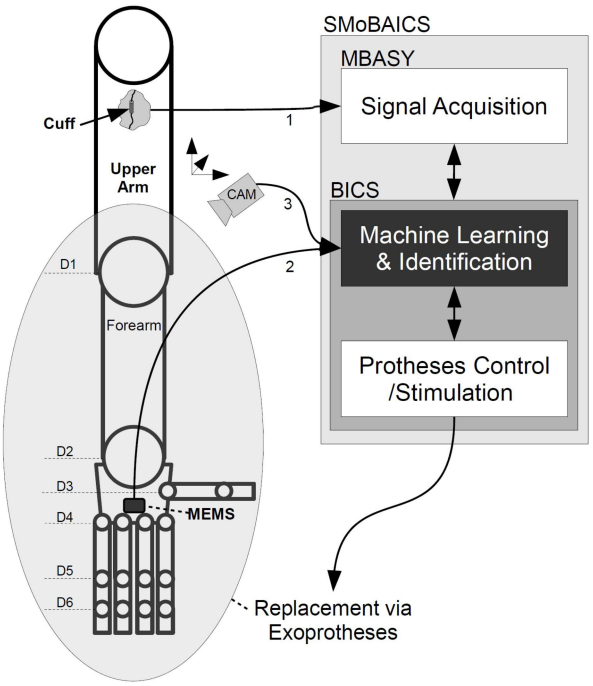

Figure 1: System Overview

Rossini, and Micera 2014) is in this project not in the focus, but the identification (Cesqui, Tropea, Micera, and Krebs 2013) of motion-based action potentials is the proposal to realize a smart minimal-invasive solution. To record ENG-signals with a very low amplitude, which are only of the order of a few microvolts, a special frontend-hardware/software system has been designed, realized in two different prototypes, introduced in (Klinger 2015) and (Klinger and Klauke 2013). In this paper the focus is on a new combined identification and verification method, taking advantage of a continuous symbiotic system. This work continues the former work about system identification presented in (Bohlmann, Klauke, Klinger, and Szczerbicka 2011), (Bohlmann, Klinger, and Szczerbicka 2009) and (Bohlmann, Klinger, and Szczerbicka 2010a).

The prototype of the Smart Modular Biosignal Acqusition, Identification and Control System (SMoBAICS), shown in Figure 1, integrates all necessary tasks (Hazan, Zugaro, and Buzsáki 2006). The biosignal acquisition is done by the Modular Biosignal Acquisition System (MBASY)-subsystem, the next generation of our own frontend-hardware/software-system. The MBASY is redesigned to get a better functionality and to optimize the modular concept (Klinger 2015). The central part of the identification process is integrated in the Biosignal Identification and Control System (BICS). It consists of two parts: the machine learning & identification and the control/stimulation from a prosthesis. While the second part is designed by state-of-the-art technology, the machine learning & identification is composed of multi-agent-based optimization algorithm and an evolutionary correlation of different types of nerve signals and of additional information like camera positioning or micro-electro-mechanical systems (MEMS). We introduce this part in more detail in section 2.

Before describing the overall function one aspect regarding the learning procedure has been taken into consideration. The objective of SMoBAICS is the action potential based control or stimulation of upper or lower limbs of handicapped human beings. SMoBAICS provides not only a base identification step (learning phase) but an ongoing supervision (operating phase). Obviously, the operating phase has to be executed on a small body mounted system but in this paper the focus is not on this system detail.

In Figure 1 a typical application is shown, the cuff electrode is implanted in the upper arm enclosing a neural bundle. The action potentials are recorded by the MBASY and passed to the BICS (1). Two additional information streams are used by the BICS for the action potential based identification: a camera-based motion capturing, used during the learning phase (3), and a motion tracking device at the end effector (e.g. the hand), used during the operational phase (2). These data streams are important for the identification.

1.2. The Symbiotic Cycle

To understand or control any type of complex process a process model is essential, an empirical process description does not provide a detailed functional and time related process specification. The process model, based on the combination of physical equations and a graph structure, allows the reconstruction of process behavior, the optimization of the entire process and a forecast of process behavior. This paper describes a method to generate a process model from scratch, without using any type of initial model description. The method is based on machine learning and symbiotic simulation and describes a type of symbiotic cycle. The model generation is a continuous process and provides therefore an adaptation to changing process parameters, like friction or bearing clearance, boundary conditions and constraints.

Based on the classification of symbiotic simulation in (Aydt, Turner, Cai, and Low 2008), (Aydt, Turner, Cai, and Low 2009), the symbiotic cycle combines a symbiotic simulation control system (SSCS), a symbiotic simulation forecasting system (SSFS), a symbiotic simulation model validation system (SSMVS) and a data driven agent based online machine learning system with a real world process (Trianni 2014).

The central challenge in this paper is on the one hand to create a system which can produce a human readable model without the existence of prior data, model or knowledge (Yang, Koziel, and Leifsson 2013). And on the other hand to be able to simulate and/or predict the behavior of the system without a known model. Both challenges presuppose each other. First it is basically a kind of chicken or the egg dilemma. The simulation system needs a model, this is produced by the machine learning system, which needs some sort of input data,

but this data is produced by the motion of the robot, finally controlled by the simulator. The basic method proposed and demonstrated in this paper is the symbiotic solution. If all steps are running in parallel the central dilemma disappears. This is what is called the symbiotic cycle. All components of the self learning system are connected by using a streaming event-driven approach. If an event which could cause an action in a different component is happening, it is immediately streamed to the corresponding component. In fact there is no macroscopic sequence or stepping between components. Everything is processed simultaneously in parallel. The machine learning module for example continuously outputs model candidates at a relatively unknown rate. The simulator then reacts by profiling the solution proposal. Clearly this could lead to a short-time overload of modules, if some burst input is generated. To minimize this effect buffering and load balancing technology are used.

2. IDENTIFICATION & MACHINE LEARNING

The machine learning and identification is the most complex module within SMoBAICS. In this paper the focus is on different verification approaches, providing a new continuous symbiotic method including machine learning.

2.1. Data Preprocessing

All real data, recorded from the cuff electrode have to be preprocessed to improve the data conditioning. The verification data generated from the NEURON-simulator can be used directly.

- Filtering: The recorded action potentials are disturbed by intrinsic noise. In addition these are overlaid by a substantial extrinsic noise, originated for example by electromyogram (EMG) from surrounding muscles. Therefore the recorded data has to be filtered with integrated analogue filter and additional digital filter.
- Re-sampling: The recorded data has two main weaknesses: The samples are asynchronous and aperiodic. In order to get a time series of data samples the following steps are performed:
    - Interpolation and FIR Filter (finite impulse response)

      For each sequence the given values are interpolated and smooth the result with a convolution.
    - Error Correction

      The interpolated data is equalized with the original samples gained from the Data Factory.
    - Down-sampling

      We pick Euclidean equidistant samples from each sequence and combine them to data samples with a time-stamp.

      During the machine process the data samples will not stay in their chronological ordering. To be able to perform time derivation, it is necessary to save the chronological neighbors for each sample. The resulting time series of equidistant data samples p consists of a time-stamp p_{time}, a vector $p_{data} = [p_{out}, p_{in}]$, with $p_{out} \in \Re$ and $p_{in} \in \Re^m$, containing the output and input data and its chronological neighbors p^{pre} and p^{post}. With P we denote the set of all such data samples. Furthermore we define the delta value $p_{in}^{\Delta} \in \Re$ with

$$(p_{\text{in}}^{\Delta}) := \frac{1}{2}\left(\frac{(p_{\text{in}}) - (p_{\text{in}}^{\text{pre}})}{p_{\text{time}} - p_{\text{time}}^{\text{pre}}} + \frac{(p_{\text{in}}) - (p_{\text{in}}^{\text{post}})}{p_{\text{time}} - p_{\text{time}}^{\text{post}}}\right),$$

$$(p_{\text{out}}^{\Delta}) := \frac{1}{2}\left(\frac{p_{\text{in}} - p_{\text{in}}^{\text{pre}}}{p_{\text{time}} - p_{\text{time}}^{\text{pre}}} + \frac{p_{\text{in}} - p_{\text{in}}^{\text{post}}}{p_{\text{time}} - p_{\text{time}}^{\text{post}}}\right).$$

2.2. Identification via Machine Learning based on Continuous Symbiotic System

The machine learning is based on evolutionary algorithms – a generic population-based metaheuristic optimization algorithm inspired by biological evolution (DeJong 2006) – embedded in a multi-stage and multi-agent implementation, shown in Figure 2. The planet structure models the environment for the populations inside the evolutionary algorithm. Every planet provides a data field, the software agents can operate on.

The number of planets is scalable, the current predetermined size is $n=9^4=6561$. Using a multiprocessor system, the number of planets have to be multiplied by the number of cores. Data acquired from the process connection are preprocessed, equal to the filling of the

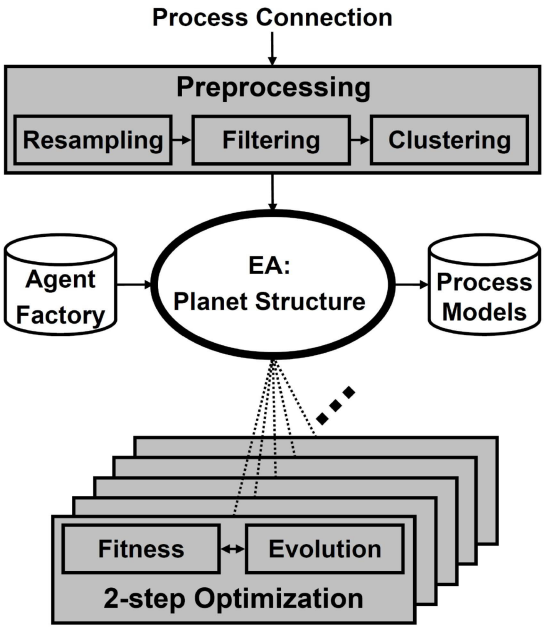

Figure 2: The architecture of the machine learning method

planet structure. The preprocessing consists of several steps to guarantee a high average information content of the data, so called data entropy. One step is an appropriate data preprocessing, described in principle in subsection 2.1. One further step is the data filling. This last step of the data preprocessing arranges the data samples on a 2D surface of a so-called planet. The surface of the planets is built in a recursive pattern of squares containing nine elements, filled meanderlike. This method leads to the planet size 9^4. This arrangement has the advantage, that the data set used for the local optimization consists of data samples, which may be spread more widely across the input sequences.

In the central part of Figure 2 the agent factory, the model library and the 2-step optimization, dedicated to every planet, is shown. The agents have 4 essential features: an age, an energy level, an area and their model function, approximating the corresponding process function. Moreover a replication mechanism is implemented, meaning the agents are able to produce a child and put it on an area. The age and the energy level are increased after each iteration. All operations an agent can perform, have an energy effort, by which the energy level is lowered, if the operation is executed. Furthermore the agents have the ability to learn from their local data and improve their model function by executing different evolutionary operations to change the structure of the model function and a local optimization algorithm to calibrate the parameters. In each iteration the software agents perform the following operations: Calculate Fitness, Move, Local Optimization, Evolutionary Operation and Nomination (The agents elect a few individuals with the highest fitness values and age on each planet to form an *Elite Population*). The Evolutionary Operation consists of

- Mutation: The agents model function gets changed randomly: Either a sub-tree of the model function is exchanged or new operations are inserted.
- Crossover: When an agent moves it may happen that the chosen area is already occupied with another individual. In this case, a sub-tree of the individuals model function is replaced by a randomly chosen, suitable sub-tree of the other agents model function.
- Replication: The agent duplicates himself.
- Global Optimization: The agents, which own enough energy or are not adult yet, optimize the parameters of their model function in the Memetic Coprocessor, explained below.

The global optimization is realized on memetic coprocessors, running on an extra processor core, executing more sophisticated algorithms for a global optimization. In the current configuration a downhill-simplex algorithm (Nelder and Mead 1965) is used. The algorithm chosen for this local parameter optimization is resource-saving, because it is executed for all agents in every iteration.

The machine learning provides the capability of running the evolutionary algorithm described above on several planets at the same time. If this is the case, some of the areas on each planet get marked as so called beam areas. After each iteration copies of all individuals placed on such an area are send to a randomly chosen area on a randomly chosen planet, provided the chosen area is not yet occupied by an agent. In the experiments 100 of the 6561 areas on every planet were marked as beam areas. Our implementation associates each planet to one processor core, on an additional processor core a universe supervisor is executed. This supervisor manages the elite population using the data from all planets and controls the termination condition. The information exchange between the cores is implemented via a non-blocking Message Passing Interface.

3. VERIFICATION APPROACHES

The verification block confirms the quality of the model and is an essential part, it helps to evaluate the model which is improved or build up during identification process. The verification strategy is based on a set of process input sequences $((x_1)_t, \dots, (x_m)_t, t \in \aleph)$ and output sequences $((y_1)_t, \dots, (y_j)_t, t \in \aleph$ and of the simulation output sequences $((z_1)_t, \dots, (z_j)_t, t \in \aleph$. The output sequences of the simulator are related to the input sequences by functional relationships $f: \in \Re^m \to \Re^j$. In principle, the verification method can be executed with synthetic data (generated by a model of the evaluated system) or live data (acquired from the physical process). We first focus on the synthetic data verification.

The Curve Fitting, presented in (Klinger and Klauke 2013), provides an open loop verification, which is not able to start the verification process without an initial model. Furthermore, this open loop verification is not able to control the verification process to increase the quality of the model. Precisely for this reason, a closed-loop verification process has been designed, the symbiotic cycle, shown in Figure 3. The system architecture follows the paradigm of the symbiotic cycle and it is based on the machine learning, introduced in subsection 2.2. Five modules form this symbiotic cycle which is application independent, the additional modules are described in the following.

3.1. Process

The process block covers all physical relations of the considered process. Analog inputs or outputs have to be transformed using analog-to-digital- or digital-to-analog-converters. The interface to the digital in-/out- signals is handled using the process data streaming protocol (PDSP) managing distributed process data flows (Bohlmann, Klinger, Szczerbicka, and Becker 2010b). This protocol is designed to be used in mixed continuous and discrete environments (Zeigler, Praehofer, and Kim 2000) referred to as hybrid. Focusing on symbiotic simulation (Fujimoto, Lunceford, and Uhrmacher 2002), PDSP is primary designed to satisfy four modes

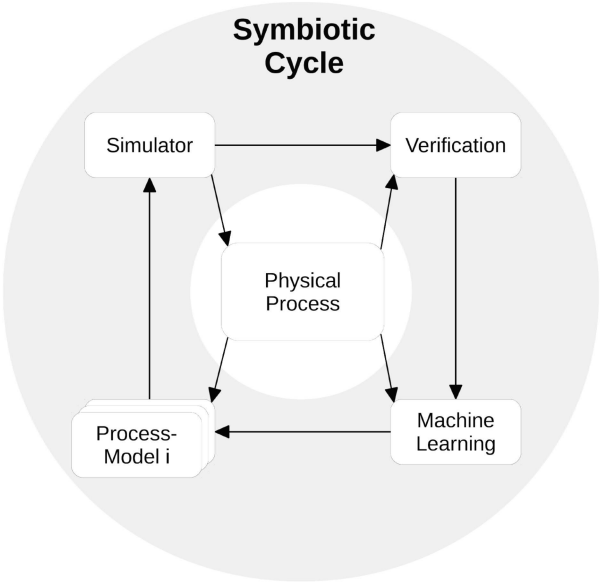

Figure 3: Symbiotic Cycle

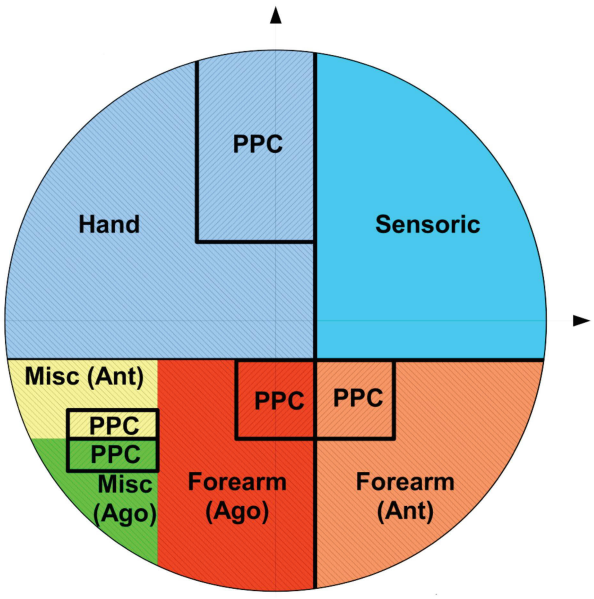

Figure 4: Nerve Bundle: Axon Model

of operation (analytic, transparent, online, prediction); here the focus is on the online mode. In this mode PDSP is used to simulate a process and transmit the results back to the process. The data is directly transmitted between the physical process and the simulator. Therefore latency is minimized although proxy servers may be necessary for large scale simulations.

3.2. Simulator

In the simulator block two different approaches are used, dependent from the application. For general purpose it is a Java based simulation system specifically designed for high speed online and symbiotic simulations. The simulator especially has online compiling capabilities, e.g. models can be compiled during runtime in memory and then dynamically injected into the simulator. It is capable to dynamically load or receive models (basically any kind of java program) and simulate multiple isolated instances in the same memory/thread context. The simulator combines Java class loading mechanism and byte code enhancing to calculate user defined metrics while processing prior structural unknown models on the fly. In combination with an OSGI framework PDSP can be directly embedded to running simulations.

For the specific application of ENG-based identification currently the well established NEURON framework for empirically-based simulations of neurons and networks of neurons is used (Carnevale and Hines 2006), (Coates, Larson-Prior, Wolpert, and Prior 2003), (Law and Kelton 2000). The different constraints, like myelin structures, all-or-none, two directions of information flow, frequency borders of the action potentials, etc. has been taken into account. We have configured the simulator and realized a complex neural bundle including our cuff electrode setup to generate verification data for several information transfer scenarios.

Therefore a cross-sectional area of the nerve bundle is part of the configuration, shown in Figure 4. This model is used for the simulation environment available to build up the axon configuration in NEURON. The action potentials used for the NEURON-simulator are derived by human arm modeling via Matlab Robotics Toolbox (Corke 2011) or using a real robot arm or prosthesis. With this model for verification it is possible to concentrate on specific muscle groups and their reactuatory answer and therefore verification pattern can be generated. The simulation environment uses the Hodgkin-Huxley model (Hodgkin and Huxley 1952) to simulate the axon internal membrane, the ion-channels and the extra-cellular space. So, the propagation of action potentials along the axons is modeled using these equations. Furthermore, the mechanisms concerning the passive membrane channels are included.

3.3. Process Model

The area provides data samples to learn from and calculate the error of the model function ($\Re^m \rightarrow \Re$) is stored in a tree representation. This function is composed of elementary operations (Schmidt and Lipson 2007), like +,−,*,/,*sin*, *sqrt* the variables $x_1, \ldots, x_m$ and a set of parameters within their model function.

According the multi-agent capability, there are several models existing. The number of currently active agents and their inner candidate function is regulated by a software PID control. It is programmed to use the available processing power in nearly optimal conditions. The best models are picked according their ability to survive multiple times longer than the mean agent population. This metric corresponds to the selection of the fittest agents. The complexity of the process models is problem-related dynamic. It depends on the number of input

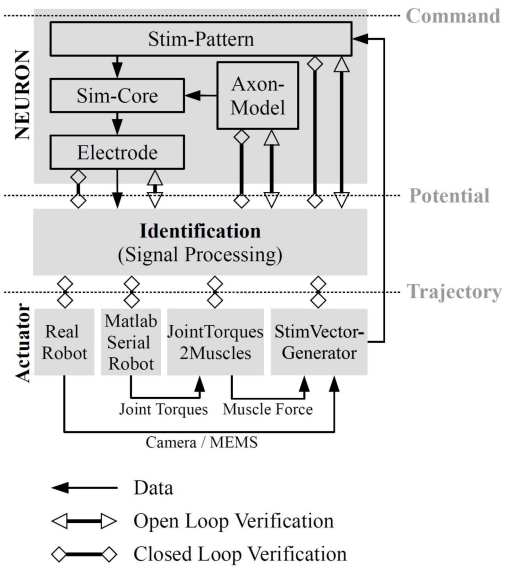

Figure 5: Open- and closed-loop verification

variables, constants and operations. The complexity is defined by counting the number of nodes in the tree representations. The differences between both verification methods are illustrated in Figure 5. The open-loop method allows a verification of the potential-level (electrode-data) against the command-level (Stim-Pattern). It is not able to generate new adequate verification patterns to improve the quality of the model behavior according to specific system states. The new method including the symbiotic cycle integrates the verification in a complex and interactive exchange of data between physical process, process model, machine learning and the simulator. The closed-loop verification provides a verification between the trajectory level and the command-level, including the potential-level. The identification block controls the generation of trajectory-related Stim-Pattern. One major advantage of this method is the fact that no initial model is necessary, the continuous symbiotic system generates it from scratch. Regarding the use of the prosthesis two alternatives are shown in Figure 5 in the actuator level: The real robot, a physical system, or a serial robot, simulated by Matlab. Both alternatives are working as the cause and effect element, closing the gap between command and trajectory level. While the serial robot provides joint torques related to a simulated trajectory, the real robot provides the trajectory information via a camera system or an integrated MEMS device (see Figure 1). To create a symbiotic online learning environment all data from the physical process is streamed via PDSP to and from a central routing software. Machine learning and the massive parallel simulation are running outside the real time domain. The control simulation, which is using the currently best known model, is running inside an embedded system in real time. Communication between the two domains basically consists of a model transmission and a movement direction proposal directed into the real time domain. Data transmission directed to the machine learning, verification and simulation is a set of streamed time series data.

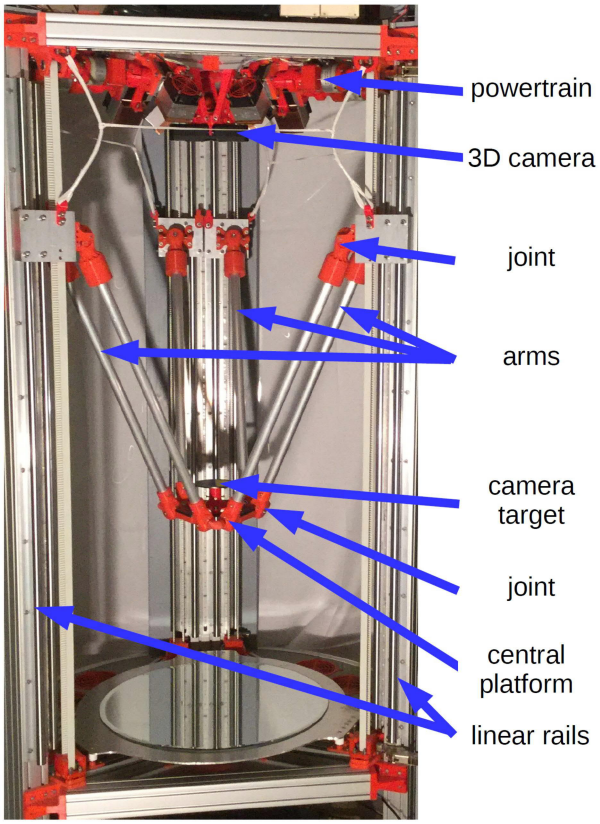

Figure 6: Demonstrator System

4. RESULTS

In this paper one key aspect of the proposed closed-loop identification method is shown. We are using the identification method to generate the model from a real robot using camera information. After the model set-up from the real robot system, this closed-loop verification can be used according Figure 5. The real robot, used in this set-up, is shown in Figure 6. To integrate a robot as a prosthesis prototype this demonstrator system, a parallel delta robot has been used. It basically consists of 6 vertical linear rails grouped into 3 pairs. These are placed around the working area in 120° spacings. Each linear axis is connected to a joint, which is connected to an arm and again to a joint. This joints are all linked to a central platform. As common to all parallel kinematic chains a move in one actuator influences the position of the central platform in all possible degrees of freedom (DOF). This 6 linear actuators are the output stage of the simulation. To be able to detect the concrete position of the system a depth camera combined with a standard 2D camera is mounted above the working area inside the robot. The depth camera used is a infrared structured light sensor. In the experiment the camera follows a round target placed in the center of the platform. Camera output (after some processing) is the position of the platform. This is a 6 channel output: 3 spatial directions and 3 rotation angles. These 6 channels are the sensor output of the robot and the input for the simulation system. All 6 sensors and 6 actuators combined add up to the input for the machine learning

part. This has been referenced in the previous chapter as p_{data}. The position of all actuators influence the position of all axis so the complete information set is required to be able to calculate an accurate prediction model. To create a symbiotic online learning environment the delta robots internal real time network is connected to a external computer. All data produced by the robotic system is streamed via PDSP to and from a central routing software. Machine learning and the massive parallel simulation are running outside the real time domain. The control simulation, which is using the currently best known model, is running inside an embedded system in real time. Communication between the two domains basically consists of a model transmission and a movement direction proposal directed into the real time domain.

To realize the symbiotic machine learning system described in this paper one central question is: Where should the symbiotic robot acquire new data? The basic idea is to collect new experimental data at a location where the possible solutions generated by the machine learning system differ the most.

We define $x_i \in \Re$ as the input variables, $p_j \in \Re$ as the constant parameter and $y_j \in \Re$ as the output variables of a suggested model. The machine learning system produces a list of candidate functions sequences $f_{e,j}(x_0, \dots, x_n, p_0, \dots, p_m) = y_j$. e is defined as the solutions index (typically e<30=e_{max}).

$$D_j = \{f_{g,i} - f_{g,j} | i \neq j \text{ and } g, h = 0, .., e_{max}\} \quad (1)$$

Now the movement direction s for data acquisition can be defined as:

$$s = \underset{d \in D_i, j=[0..6]}{\operatorname{argmax}} \|\nabla d\|_1 \quad (2)$$

This direction s is calculated by the simulator on the fly while processing new input data and transmitted to the robotic system. The simple idea behind this is to acquire new input data where model candidates tend to have different results. This leads to a continuous hypothesis filtering in the elite generation.

The basic challenge of the machine learning system can also interpreted a global non linear optimization problem. The concept behind the above formulated feedback metric is to continuously adapt the target function, while machine learning is running. The adaption process described is on the other hand based on the output of the candidate functions $f_{e,j}(x_0, \dots, x_n, p_0, \dots, p_m) = y_j$ evaluated by the online simulation system. This is again what is defined as the symbiotic cycle. If the global target is the deepest valley on the multidimensional target function, then the symbiotic circle will force secondary minima to increase their value by sampling new contradictory data from the physical system. The only valleys not affected are the global optima formed by different possible formulations of a globally valid and correct process model. Data transmission

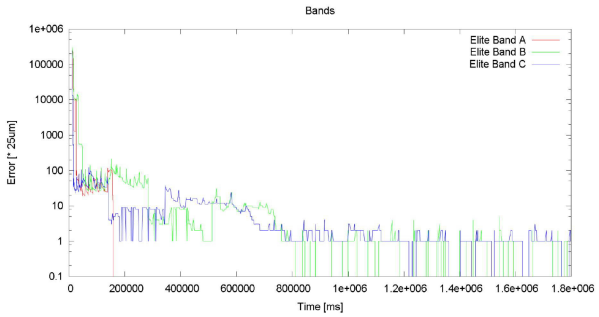

Figure 7: Error band for actuators A, B, C

directed to the machine learning, verification and simulation is a set of streamed time series data. All calculations outside the real time domain are processed on two quad Intel Xeon E7-8860v3 compute systems (128 logical cores) with 1TB of DDR4 RAM each. The real time control System located in the head box of the physical system consists of 14 Arm Cortex M4 Microcontrollers and three 8 Core Arm Cortex-A7 Processors. Local compute power is therefore relatively small compared with the cloud connected machine learning modules. To demonstrate the emergent effects arising from the combination of all modules of the symbiotic circle the same machine learning system has been used as in (Bohlmann, Klinger, Szczerbicka, and Becker 2010b).

It takes some time at the beginning to acquire enough input data to generate a start-up model from scratch. Secondly the error does not progressively decrease as often found in offline machine learning. This is caused by the feedback metric sampling new data at positions with low performance of some model candidate. This is a direct result from new online data injected to the machine learning progress. These spikes for the three actuators are depicted in Figure 7, presenting the decreasing error band for the 3 actuators A, B and C. The interesting aspect here is, that the peaks sometimes but in most cases not correspond to others. We found that this is a direct result from the *argmax* operator in formula 2. It is basically caused by the selection of one pair out of all actuators to determine the robotic movement direction until a different pair has a higher rating.

By far the most amazing aspect is the comparison of the offline performance (Bohlmann, Klauke, Klinger, and Szczerbicka 2011) of the system and the online system interacting with the real world robot. While the offline machine learning system is only capable to identify models with a tree complexity of around 19 nodes with non good success rate, the online system identifies a model with complexity of 33 nodes. Furthermore as described in (Bohlmann, Klinger, Szczerbicka, and Becker 2010b) the machine learning modules offline performance decreases dramatically if additional noise is present in the input data. Obviously, experiments described in this paper additionally and inherently contain measuring noise through the use of a real physical system. The direct and automated online interaction of online simulation, verification, machine learning and physical process produce far better performance than each component alone could produce.

5. SUMMARY AND FURTHER WORK

The SMoBAICS acquisition system of motion-based action potentials in neural bundles for exo-prostheses control or for handicapped limb simulation provides an integrated solution from action potential recording up to the identification procedure. This paper focuses on a new method based on a continuous symbiotic cycle, providing a closed-loop approach. While an open-loop approach helps to identify well-known processes, improving the overall model quality, the closed-loop approach, using the symbiotic cycle, helps to generate a physical process model from scratch and forms an adaptable and scalable identification environment.

As it is continuously present, the robotic controller can react to changes in the system. The most valuable result in fact is that model complexity which could be learned from a real world process is clearly higher using a continuously interacting system. This continuous symbiotic system, where different modules, like machine learning, simulator and process models are interacting with a physical or technical process, improves the identification progress and opens the symbiotic simulation to applications from biotechnology.

The further work has the following key aspects:

- Evaluation of the whole identification process and integrating of the missing elements using the continuous symbiotic cycle.
- Evaluating the identification with regard to quality and performance.
- Adapting the symbiotic cycle to a clinical environment, to replace the Matlab-based part and to integrate the identification into a learning environment and the concerning applications.

REFERENCES

Aydt, H., Turner, S. J., Cai, W., and Low, M. Y. H. (2008a). Symbiotic simulation systems: An extended definition motivated by symbiosis in biology. In *Proceedings of the 22nd Workshop on Principles of Advanced and Distributed Simulation*, PADS '08, pages 109–116, USA. IEEE Computer Society.

Aydt, H., Turner, S. J., Cai, W., and Low, M. Y. H. (2008b). Symbiotic simulation systems: An extended definition motivated by symbiosis in biology. In *Proceedings of the 22Nd Workshop on Principles of Advanced and Distributed Simulation*, PADS '08, pages 109–116, Washington, DC, USA. IEEE Computer Society.

Aydt, H., Turner, S. J., Cai, W., and Low, M. Y. H. (2009). Research issues in symbiotic simulation. In *Proceedings of the 2009 Winter Simulation Conference M. D. Rossetti, R. R. Hill, B. Johansson, A. Dunkin, and R. G. Ingalls, eds.*

Bohlmann, S., Klauke, A., Klinger, V., and Szczerbicka, H. (2011). Model synthesis using a multi-agent learning strategy. In *The 23rd European Modeling & Simulation Symposium (Simulation in Industry)*, Rome, Italy.

Bohlmann, S., Klinger, V., and Szczerbicka, H. (2009). HPNS - a Hybrid Process Net Simulation Environment Executing Online Dynamic Models of Industrial Manufacturing Systems. In *Proceedings of the 2009 Winter Simulation Conference Rossetti, Hill, Johansson, Dunkin, and Ingalls, eds.*

Bohlmann, S., Klinger, V., and Szczerbicka, H. (2010a). System Identification with Multi-Agent-based Evolutionary Computation Using a Local Optimization Kernel. In *The Ninth International Conference on Machine Learning and Applications*, pages 840–845.

Bohlmann, S., Klinger, V., Szczerbicka, H., and Becker, M. (2010b). A data management framework providing online-connectivity in symbiotic simulation. In *24th EUROPEAN Conference on Modelling and Simulation, Simulation meets Global Challenges*, Kuala Lumpur, Malaysia.

Carnevale, N. T. and Hines, M. L. (2006). *The NEURON Book*. Cambridge Univ. Press, New York, NY, USA.

Cesqui, B., Tropea, P., Micera, S., and Krebs, H. (2013). Emg-based pattern recognition approach in post stroke robot-aided rehabilitation: a feasibility study. *Journal of NeuroEngineering and Rehabilitation*, 10(1).

Coates, T.D., J., Larson-Prior, L., Wolpert, S., and Prior, F. (2003). Classification of simple stimuli based on detected nerve activity. 22(1):64–76.

Corke, P. (2011). *Robotics, Vision and Control - Fundamental Algorithms in MATLAB®*, volume 73 of *Springer Tracts in Advanced Robotics*. Springer.

De Jong, K. A. (2006). *Evolutionary Computation: A Unified Approach*. MIT press.

Fujimoto, R., Lunceford, D., Page, E., and Uhrmacher, A. (2002). Technical report of the dagstuhl-seminar grand challenges for modelling and simulation. Technical Report No. 02351, Schloss Dagstuhl, Leibniz-Zentrum für Informatik, Wadern, Germany.

Gold, C., Henze, D. A., and Koch, C. (2007). Using extracellular action potential recordings to constrain compartmental models. *Journal of Computational Neuroscience*, 23(1):39–58.

Hazan, L., Zugaro, M., and Buzsáki, G. (2006). Klusters, NeuroScope, NDManager: A free software suite for neurophysiological data processing and visualization. *J Neurosci Methods*, (155):207–216.

Hodgkin, A. and Huxley, A. (1952). A quantitative description of membrane current and its application to conduction and excitation in nerve. *Journal of Physiology*, 117:500–544.

Klinger, V. (2015). Biosignal acquisition system for prosthesis control and rehabilitation monitoring. In Bruzzone, A., Frascio, M., Novak, V., Longo, F.,

Merkuryev, Y., and Novak, V., editors, *4nd International Workshop on Innovative Simulation for Health Care (IWISH 2015)*.

Klinger, V. and Klauke, A. (2013). Identification of motion-based action potentials in neural bundles using an algorithm with multiagent technology. In Backfrieder, W., Frascio, M., Novak, V., Bruzzone, A., and Longo, F., editors, *2nd International Workshop on Innovative Simulation for Health Care (IWISH 2013)*.

Law, A. M. and Kelton, W. D. (2000). *Simulation Modeling and Analysis*. McGraw-Hill.

Micera, S., Carpaneto, J., and Raspopovic, S. (2010a). Control of hand prostheses using peripheral information. *IEEE Reviews in Biomedical Engineering*, 3:48–68.

Micera, S., Citi, L., Rigosa, J., Carpaneto, J., Raspopovic, S., Pino, G. D., Rossini, L., Yoshida, K., Denaro, L., Dario, P., and Rossini, P. M. (2010b). Decoding information from neural signals recorded using intraneural electrodes: Toward the development of a neurocontrolled hand prosthesis. *Proceedings of the IEEE*, 98(3):407–417.

Nelder, R. and Mead, J. (1965). A simplex method for function minimization. *Computer Journal*, 7(4):308–313.

Neymotin, S., Lytton, W., Olypher, A., and Fenton, A. (2011). Measuring the quality of neuronal identification in ensemble recordings. *J Neurosci*, 31(45):16398–409.

Raspopovic, S., Capogrosso, M., Petrini, F. M., Bonizzato, M., Rigosa, J., Di Pino, G., Carpaneto, J., Controzzi, M., Boretius, T., Fernandez, E., Granata, G., Oddo, C. M., Citi, L., Ciancio, A. L., Cipriani, C., Carrozza, M. C., Jensen, W., Guglielmelli, E., Stieglitz, T., Rossini, P. M., and Micera, S. (2014). Restoring Natural Sensory Feedback in Real-Time Bidirectional Hand Prostheses. *Science Translational Medicine*, 6(222).

Schmidt, M. and Lipson, H. (2007). Comparison of tree and graph encodings as function of problem complexity. In *GECCO '07: Proceedings of the 9th annual conference on Genetic and evolutionary computation*, pages 1674–1679, New York, NY, USA. ACM.

Trianni, V. (2014). Evolutionary robotics: model or design? *Frontiers in Robotics and AI*, 1:13.

Yang, X.-S., Koziel, S., and Leifsson, L. (2013). Computational optimization, modelling and simulation: Recent trends and challenges. *Procedia Computer Science*, 18:855 – 860.

Zeigler, B. P., Praehofer, H., and Kim, T. G. (2000). *Theory of Modeling and Simulation: Integrating Discrete Event and Continuous Complex Dynamic Systems*. Academic Press, San Diego, USA, 2 edition.

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TOWARDS STANDARDS BASED HEALTH DATA EXTRACTION FACILITATING PROCESS MINING

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ABSTRACT
As an evidence based business process analysis method, process mining can be used to investigate variations in clinical practice and delivery of care. However, to enable cross-organizational comparative analysis, healthcare institutions need a common ground for the description and representation of health data. In this work, we analyze different approaches, to describe clinical and patient pathways. The Healthcare Reference Model represents a bottom-up approach, the HL7 v3 RIM as a generic health information model represents a top-down approach and HL7 FHIR, the newest standard of the HL7 family stands in-between. We highlight similarities and differences according to interoperability and process mining tasks. We conclude that a standards (RIM) based top-down approach, and the derived FHIR approach respectively, is able to provide similar insights and, on top of that, operational support for the ETL process on all interoperability levels.

Keywords: *Process Mining, Data Extraction, Semantic Interoperability, Evidence Based Medicine*

1. INTRODUCTION

Clinical pathways are management tools used to define the best process in a healthcare organization, using the best procedures and timing, to treat patients with specific diagnoses or conditions according to evidence-based medicine (Panella, Marchisio and Di Stanislao 2003).
For the development of clinical pathways and medical guidelines a comparative analysis of the existing approaches is useful. (Partington et al. 2015) propose the application of process mining as *an evidence-based business process analysis method* to investigate variations in clinical practice and delivery of care across different hospital settings.
However, existing approaches to use process mining for comparative analysis of healthcare processes are based on data sources within one organization. More precisely the formal representation and the semantics (including code systems and value sets) of the different data sources were basically the same (Partington et al. 2015; Mans et al. 2008). To gain insight into and enable comparative analysis of clinical practice and delivery of care across different organizations, a preceding step to identify and reach *common ground* is necessary.
In the recent book *Process Mining in Healthcare* the authors describe a *healthcare reference model* (HRM) that aims to help locating the needed data in healthcare information systems and thus facilitate the data extraction for process mining (Mans, van der Aalst and Vanwersch 2015). This data model can be seen as the *common ground*, and in their *Use Case 5: Healthcare Process Comparison* the authors also use it to compare processes of two different hospitals.

1.1. Prerequisites for Process Mining

Process mining algorithms work on event logs with a certain structure. Event logs must contain only data related to a single process and it must be ensured that all events in the log can be related to this process. Moreover, each event in the log must represent an activity and refer to a single process instance (case). To get the data out of the (distributed) data sources and to put them in this structure, preprocessing steps are necessary.
The Extract, Transform and Load (ETL) steps preceding the actual process mining tasks describe: (a) extraction data from outside sources, (b) transforming it to fit operational needs (dealing with syntactical and semantical issues while ensuring predefined quality levels), and (c) loading it into the target system, e.g. a data warehouse or relational database (Van der Aalst 2011).

1.2. Structure of this Work

In the following sections, this paper presents a different approach to reach common ground based on established healthcare interoperability standards. In section 2,

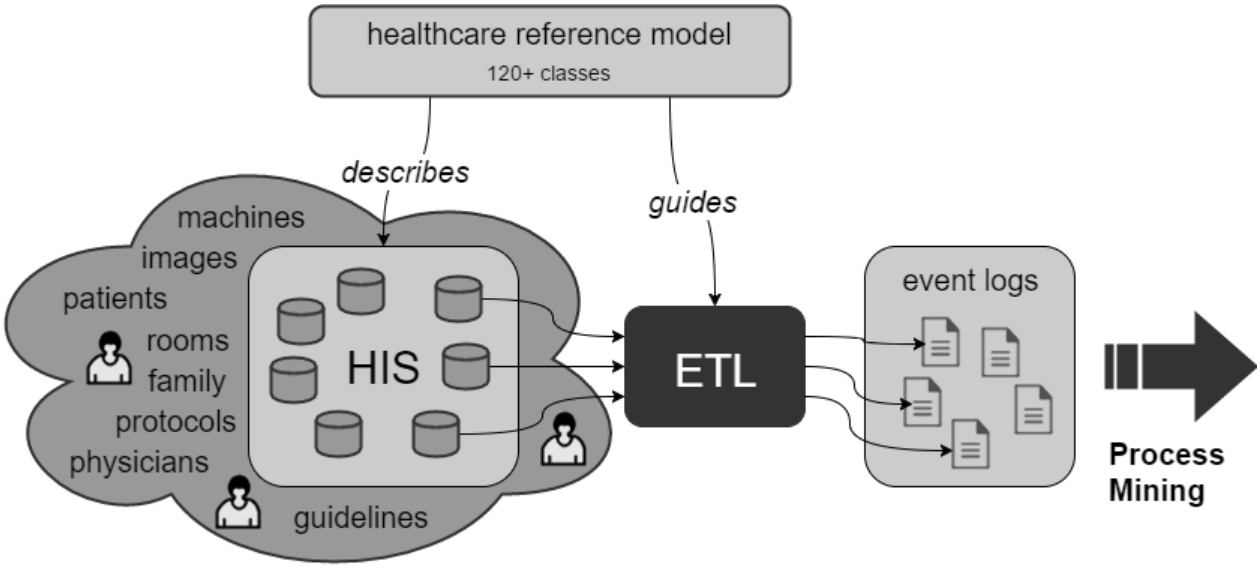

Figure 1: The healthcare reference model in context of process mining. It is used as a starting point for locating the data and extracting event logs, guiding the *Extract, Transform and Load* process (Mans, van der Aalst and Vanwersch 2015).

Background, the referenced standards and their applications in data modelling as well as the development approach of the HRM are described. Section 3, Methods, defines the analytical approach used in this research and explains the interoperability levels used to compare the various approaches. Section 4, Results and Discussion, describes the analyzation results of the various approaches with focus on the ability of the models to describe patient pathways. The results are compared results by their ability to integrate data from different sources. Section 5, Conclusion, summarizes important findings and emphasizes the additional options of a standards-based approach.

2. BACKGROUND

This section presents interoperability levels necessary for integrated healthcare and the modelling approaches HRM, RIM and FHIR, which are analyzed in this paper.

2.1. Levels of Interoperability

National as well as international initiatives for information integration in healthcare aim at the increase of interoperability of information systems and at minimizing integration efforts (Norgall 2003, Sunyaev et al. 2008). The term *interoperability* denotes the ability of systems to collaborate. Combining the definitions of (Heitmann and Gobrecht 2009) and (Serrano et al. 2015) we can defer three levels of interoperability, which incorporate, among others, the following characteristics:

- Exchange of meaningful, actionable information between two or more systems across organizational boundaries (*technical interoperability*)
- A shared understanding of the exchanged information (*semantic interoperability*)
- An agreed expectation for the response to the information exchange and requisite quality (reliability, fidelity, security) of services and processes (*process interoperability*).

Integrated care and the achievement of high quality healthcare over institutional borders require all three levels of interoperability between different healthcare providers.

2.2. Healthcare Reference Model

The HRM was specifically designed for the healthcare domain to guide the ETL steps and to help locating the data needed for process mining. Figure 1 shows the role of the HRM in the data preparation.

It was developed using a two-step approach as described in (Mans, van der Aalst and Vanwersch 2015). First, the data model of a running *i.s.h.med* hospital information system (HIS) was reverse engineered based on the actual database table structure, expert interviews and hands-on inspection. Secondly, the model was validated via interviews with HIS professionals of other hospitals.

This resulted in a model described in terms of a UML class diagram comprising 122 classes. The classes are grouped in several sub-models such as *General Patient and Case Data*, *Radiology* and *Document Data*.

The developers of the HRM do not claim completeness of the model since HISs of different vendors may contain data not present in the model. However the key elements needed for process mining should be included (Mans, van der Aalst and Vanwersch 2015).

2.3. Reference Information Model

HL7 standards have been specifically developed for the health sector. They define the exchange of messages, document based communications as well as cooperating services, their implementation and necessary infrastructural services (Benson and Grieves 2016).

Core of HL7 standards is the Reference Information Model (RIM), which is a generic healthcare specific information model. The base of this model are four core classes (Act, Entity, Role and Participation) and two

additional classes (ActRelationship and RoleLink), as shown in Figure 2.
The goal is the development of a uniform understanding of objects and processes in the healthcare environment. The use of RIM provides specifications to structure, type, content as well as semantics, used vocabulary and underlying processes necessary for data transfer and interoperability, following a top-down approach. Well established standards like document-based exchange standard HL7 Clinical Document Architecture (CDA), are based on Refined Message Information Models (R-MIM), which are derived from the HL7 RIM.

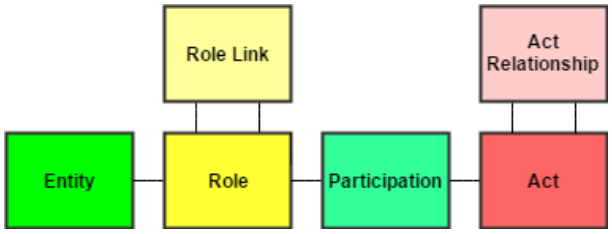

Figure 2: The backbone of the RIM with the main classes *Act*, *Role* and *Entity* and the association classes *Participation*, *Role Link* and *Act Relationship* (Benson and Grieves 2016).

For the representation of clinical and patient pathways HL7 proposes the care plan model, for which a layered modelling approach was applied to allow separation of business, information and interoperability requirements. This is achieved by separating the Care Plan model in three distinctive layers (HL7 2016):

2.3.1. Care Plan Conceptual Model

The conceptual model identifies necessary concepts and the relationships between them. These are directly derived from high level business requirements and thus build the foundation for the consecutive layers (HL7 2016). More specifically the conceptual model consists of an abstract concept *Plan* that is associated with further concepts, e.g. *Care Giver*, *Patient*, *Provider*, *Activity*.

2.3.2. Care Plan Organizing Framework for Coordination of Care Models

According to Health Level 7 (HL7 2016), the Care Plan Organizing Framework is a meta-model for coordination of care interaction and collaboration. Thus, the model defines relationships between a subset of the concepts defined in the conceptual model.

2.3.3. Care Plan Logical Information Model

The final layer in the Care Plan Model adds data properties to the concepts defined in the predeceasing layers. This further allows to capture information relevant for dynamic coordination of care interactions and point in time data exchange (HL7 2016).
The resulting care plan structure is thus applicable in a wide range of scenarios and use cases, consisting of discipline- or treatment -specific plans as well as comprehensive multidisciplinary plans, e.g. in case of tumor board review meeting (HL7 2016).

An implementation of the Care Plan Model defined by HL7 is currently developed as part of HL7s standard Fast Healthcare Interoperability Resources and the *CarePlan* resource respectively.

2.4. Fast Healthcare Interoperability Resources

Fast Healthcare Interoperability Resources (*FHIR*) is a resource-based data exchange standard for healthcare information. FHIR Resources contain mapping information to the HL7 RIM, defining which fields of a resource correspond to which RIM concept.
FHIR is organized in different levels building upon each other:

- Level 1 – The basis of the standard, such as the API description, Data Types and Data Formats.
- Level 2 – Security and Implementer information as well as Terminology Bindings and Conformance Resources such as Structure Definitions describing FHIR Resources.
- Level 3 – Contains the basis for real world use-cases such as the Patient and Practitioners.
- Level 4 – Deals with data exchange in healthcare including clinical, diagnostic, medical, financial and workflow data.
- Level 5 – Describes clinical reasoning and contains resources enabling automation in that sector.

FHIR follows the Pareto Principle, better known as the 80/20 rule, and thus defines only the data exchange information 80% of identified use cases require. Specializations for the other 20% that may be required, can be modeled by implementers using *Extensions* and *Profiles* (Benson and Grieves 2016).
FHIR resources can be viewed in different formats, such as a Structural View, UML, XML, JSON and Turtle for understanding and rapid prototyping. All resources, which are currently defined in HL7 FHIR, are listed in the current STU 3 version (HL7 2017). FHIR is being updated regularly, with the next release planned in 2018.

3. METHODS

This section describes how the HRM and the partially RIM-based HL7 FHIR are used to model clinical and patient pathways. Furthermore, it describes how the various concepts are analyzed using the interoperability levels.

3.1. Using HRM to Model Pathways

For the HRM the definition and execution of pathways is described using 10 UML classes (see Figure 3). A pathway (*pathway*) consists of multiple items (*pathway item*) which may be connected to each other (*connection*). A pathway is executed for a patient (*patient pathway*) and information about each performed step is recorded (*step of patient pathway*). Finally, each performed step may be linked to a service that is executed for the patient (*services performed*) (Mans, van der Aalst and Vanwersch 2015).

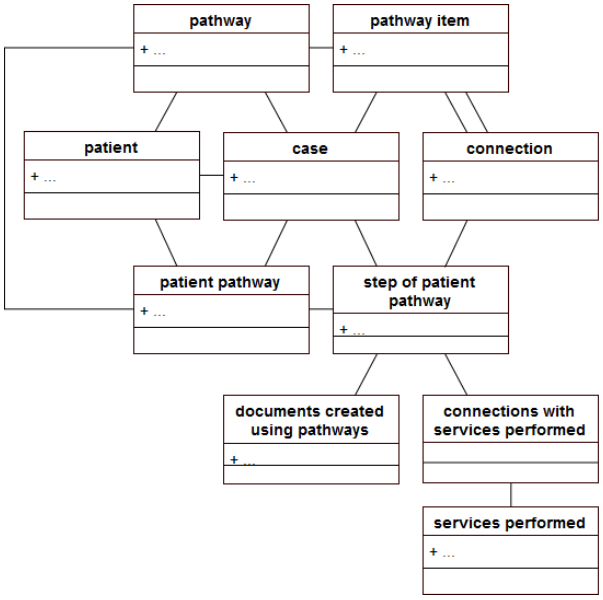

Figure 3: The UML classes used to describe clinical pathways in the HRM. The original figure in (Mans, van der Aalst and Vanwersch 2015, p49) also contained the ~150 attributes of those classes and provides cardinalities for the relations.

3.2. Using HL7 FHIR to Model Pathways

Using FHIR, the definition of an abstract clinical pathway is modelled with the *PlanDefinition* resource. This resources describes a goal that shall be achieved and defines a set of actions to explain what has to be done stepwise to achieve that goal. Actions have a timing when they can/should occur, as well as trigger definitions and conditions if and when they are applicable. Furthermore, each action has participants, explaining who is involved in the action.

Highly complex clinical pathways can also be described with the *PlanDefinition* as each action can have relations to other actions (HL7 2017). The *PlanDefinition* represents an abstract concept of what should happen in a medical pathway. It does not relate to a specific context such as actual patients or groups of persons.

3.2.1. Modeling Context-specific Pathways

To specify a *PlanDefinition* with a context, such as one real patient to be treated, the *CarePlan* resource can be used. The CarePlan is often based on a *PlanDefinition* (as seen in Figure 4), however it is allowed to modify the steps in the *PlanDefinition* as needed for treatment of the patient. In addition to representing a specific plan for a patient, or group of patients, it also, indirectly, documents what actually happens during execution of the *CarePlan* and accompanying treatment of the *CarePlan*. Similarily to the *PlanDefinition* a *CarePlan* contains a list of steps, here called activity, which describe activities to be performed. Each activity can have a template of what is going to happen, in the form of resource drafts, or alternatively contains the resource that documents what happened, such as a *MedicationRequest* documenting the administration of a medication, or an *Appointment* for the next treatment. Unlike the *PlanDefinition*, the steps in a *CarePlan* have no relation to each other (HL7 2017).

3.2.1. Using Security Details for Modeling

In addition to the *CarePlan*, which documents steps on a higher level, FHIR contains specifications for security auditing which can be used for a fine-grained view of a taken medical pathway. The *AuditEvent* resource documents every single access to a FHIR resource according to the Five Ws (Who, What, When, Where, Why). Additionally, the *Provenance* resource tracks similar information when a resource is being modified (HL7 2017).

3.3. Analyzation Based on Interoperability Levels

Using pre-defined use cases and based on the interoperability levels described in section 2.4, the HRM approach and the FHIR approach are analyzed how they add semantic information to the models and whether they support the ETL process. To achieve high quality healthcare over institutional borders, all three levels of interoperability defined in section 2.4, are needed between different healthcare providers.

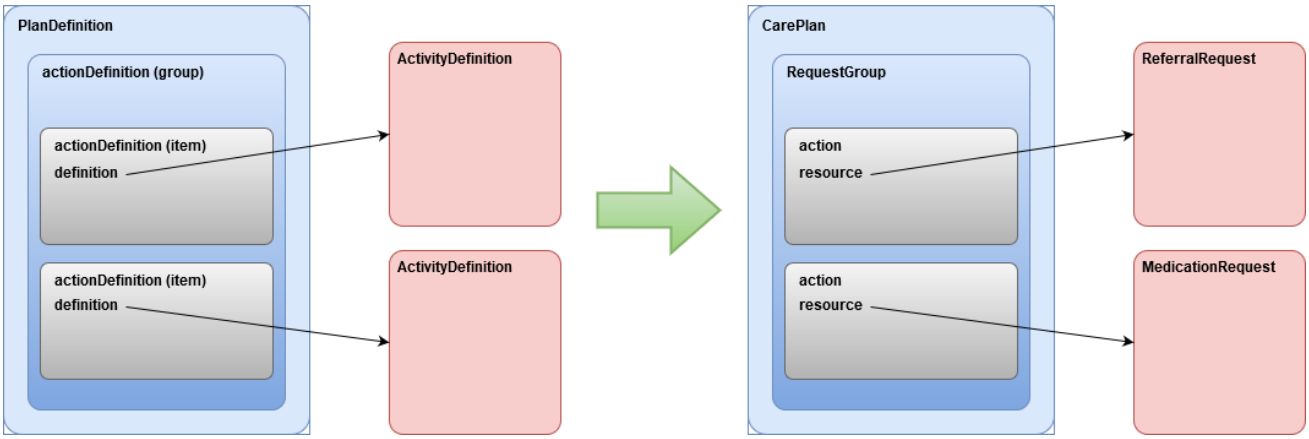

Figure 4: *PlanDefinition* groupings of actions and definitions of these actions in relation to the *CarePlan* groupings and actions. As can be seen, a *PlanDefinition* contains only abstract definitions of what should happen, while the *CarePlan* contains references to activities relating to a patient such as a *Referral* or *Medication* (HL7 2017).

Since technical interoperability has been the focus of standards organizations, alliances and consortia for many years, standards and implementations supporting this level of interoperability are generally available. Strategies for informational interoperability, however, which includes the whole area of semantic and process interoperability, are less mature (Serrano et al. 2015). Thus, we focus on these types of interoperability for the comparison of the various modeling approaches.

4. RESULTS AND DISCUSSION

Based on existing use cases and using the methods described in section 3, the HRM approach and the FHIR approach are analyzed concerning semantic interoperability, especially how they add semantic information to the models, and process interoperability with focus on whether they support the ETL process.

4.1. Analyzation of the HRM

The analyzation of the HRM is based on six use cases listed by (Mans, van der Aalst and Vanwersch 2015), where data described via the HRM was gathered from hospitals and used for process mining tasks like model discovery, conformance checking, bottleneck analysis and comparative analysis.

The HRM is instrumental in locating the data needed and facilitating the actual extraction. It supports the ETL process by giving the analysts an idea about what kind of process-related data can be found in a HIS.

The abstract HRM does not directly refer to the database structure and thus does not support the operation of *Extracting* of data (Mans, van der Aalst and Vanwersch 2015). Furthermore, the HRM model does not explicitly refer to code lists, structured value sets or nomenclatures. Attributes listed in the UML classes are identified by name, the semantics for those attributes are not provided in the textual description of the models (Mans, van der Aalst and Vanwersch 2015).

4.2. Analyzation of the HL7 FHIR

The FHIR approach was analyzed using a system for Multidisciplinary Team Meetings (MDTM) as described in (Krauss et al. 2017). MDTM are modeled in HL7 FHIR using the *PlanDefinition* resource. The models are then automatically transformed into the Business Process Model Notation (BPMN) and executed with a Workflow Engine. The process is documented using the *CarePlan* resources as well as FHIR *Auditing*. An ETL process, as described in the preceding section, could generate XES Event Logs, subsequently enabling Process Mining.

FHIR implicitly enables the entire ETL process. The *Extraction* from a data source is a given for any healthcare system implementing the FHIR standard, as the FHIR API allows reads and searches on resources.

The *Transformation* process can be executed directly in FHIR. In addition to the *ConceptMap* which allows semantic transformations, the *StructureMap* allows the mapping of any FHIR Resource to (or from) any other *Concept* defined by a *StructureDefinition*. This allows the implementer the definition of *StructureDefinitions* tailored to the exact requirements of the process-mining target. From there the *StructureMap* can describe how a regular FHIR resource can be transformed into the required structure – e.g. the eXtensible Event Stream (XES) used in recent process mining tools (Verbeek et al. 2010). Since the *StructureMap* contains machine-executable rules for transformation this mapping can be done fully-automated in a standardized way.

The *Loading* of the transformed resources can be achieved in several different ways. For one the FHIR API once again allows the access to the transformed resources similar to the *Extraction* process. Alternatively the data-mining application can use the FHIR *Subscription* service to receive push messages while the process is executed. In another push-based approach one can create a FHIR *Operation* that publishes the transformed resources directly to the data mining application.

Machine readable semantics of FHIR resources are handled through *Codings* that represent fields of resources, similar to *Codings* in the HL7 RIM. Each *Coding* consists of a *System* that defines the Code, the actual *Code* for machine-readability, and a *DisplayName* for human-readability. HL7 FHIR uses LOINC, SNOMED CT, HL7v3, ICD-10, and DICOM among others (HL7 2017).

FHIR enables the restriction of allowed values in a *Coding*, and often provides default sets, or enforces usage of a specific set. This is documented in the *ValueSet* resource which groups *Codings* into a set. To enable semantic interoperability between different *Codings* the *ConceptMap* Resource exists to define unidirectional mappings between *ValueSets*. In addition, FHIR defines a *Terminology Service* specification that uses these resources to enable usage and transformation between *ValueSets* (HL7 2017).

4.3. Comparison of the interoperability status

The described models allow the interaction of technical components and systems. Further, they enable a larger interconnected system capability that transcends the local perspective of each participating subsystem, which complies to the technical interoperability defined by (Serrano et al. 2015).

Since the HRM model does not explicitly refer to code lists and semantic details are neither provided in the model definition nor description, semantic interoperability can hardly be achieved in an automated way using the HRM.

Using FHIR, semantic interoperability is achieved through common information models and the terminology service, thus enabling process definitions in a certain domain as well as across various domains or communities. Besides technical standards, agreements are essential, how medical and domain specific terminologies are used, which have to be maintained and further developed over time. This way it is possible to relate pathways across various healthcare institutions, while preserving the intended meaning, which conforms

to the definition of semantic interoperability in (Heitmann and Gobrecht 2009).

The FHIR resources described in section 3.2 allow the definition (*PlanDefinition*, *CarePlan*) as well as the documentation (coarse granularity: *CarePlan*; fine granularity: *AuditEvent*, *Provenance*) of a medical pathway. This also allows a comparison between what should happen versus what actually did happen, which can be used to further process interoperability as well as check, compare and evaluate clinical pathways in and across institutions.

5. CONCLUSION

We compared the HRM and FHIR approaches on a conceptual basis and analyzed their ability to describe clinical and patient pathways. Furthermore, we analyzed how the models and their design approaches support the ETL process to prepare data from different sources for subsequent Process Mining. By analyzing the different approaches and their implications regarding the support of the ETL process, the use cases for the models become apparent. In the Epilogue of (Mans, van der Aalst and Vanwersch 2015) the authors highlight the importance of the HRM to *reason about questions that may or may not be answered using process mining*. Moreover the HRM produces *awareness* of the data present in a hospital.

We conclude that a standards (RIM) based top-down approach, and the derived FHIR approach respectively, is able to provide similar insights and, on top of that, operational support for the ETL process on all interoperability levels. As described above, the main reason for that is the ability to (automatically) integrate data from different sources by taking their semantic properties into account.

Further research on the implementation of a FHIR-based ETL process is necessary. The authors plan a case study with data from the MDTM system described in (Krauss et al. 2017).

REFERENCES

Benson, T. and Grieve, G., 2016. Principles of Health Interoperability: SNOMED CT, HL7 and FHIR, Springer International Publishing, pp. 243-264

Chelsom, J. et al., 2015. Document-Driven Care Pathways Using HL7 CDA. In: eTELEMED 2015: The Seventh International Conference on eHeatlh, Telemedicine, and Social Medicine, Lisbon, Portugal.

Heitmann, K. U. and Gobrecht K., 2009. HL7 Communincation standards for the healthcare system (in German). Köln: LUP AG Lithographie & Printproduktion.

HL7, 2017. FHIR Release 3 (STU) Resource Index. Available from: http://hl7.org/fhir/resourcelist.html [accessed 14 April 2017]

HL7, 2016. HL7 Version 3 Domain Analysis Model: Care Plan, Release 1, HL7 Informative Document

Krauss O., Holzer K., Schuler A., Egelkraut R., and Franz B., 2017. Challenges and approaches to make multidisciplinary team meetings interoperable – the KIMBo project. Stud Health Technol. Inform. 2017, 236, pp. 63-69.

Mans, R., van der Aalst, W. and Vanwersch, R. J., 2015. Process Mining in Healthcare: evaluating and exploiting operational healthcare processes. Heidelberg Springer.

Mans, R., Schonenberg, H., Leonardi, G., Panzarasa, S., Cavallini, A., Quaglini, S. and van der Aalst, W. 2008. Process mining techniques: an application to stroke care. Studies in health technology and informatics, 136, 573.

Norgall, T., 2003. Communication standard for health telematics: status and outlook (in German), in Proceedings e-Health 2003.

Panella, M., Marchisio, S. and Di Stanislao, F., 2003. Reducing clinical variations with clinical pathways: do pathways work? In: International Journal for Quality in Health Care, 15(6), 509-521.

Partington, A., Wynn, M., Suriadi, S. and Ouyang, C., 2015. Process mining for clinical processes: a comparative analysis of four Australian hospitals. In: ACM Transactions on Management Information Systems (TMIS), 5(4), 19

Serrano, M. et al., 2015. Semantic Interoperability Release 2.0, AIOTI WG03 - IoT Standardisation, Alliance for Internet of Things Innovation.

Sunyaev, A., Schweiger, A., Leimeister, L.M. and Krcmar, H., 2008. Software Agents for integration of information systems in healthcare (in German), in Proceedings of e-Health 2008, pp. 1455-1466.

Van der Aalst, W. M., 2011. Getting the Data. In: Process Mining, Springer Berlin Heidelberg, 95-123.

Verbeek, H. M. W., Buijs, J. C., Van Dongen, B. F. and van Der Aalst, W. M., 2010. XES, XESame, and ProM 6. In: CAiSE Forum Vol. 72, pp. 60-75

HEMODYNAMICALLY NON-SIGNIFICANT CORONARY ARTERY STENOSIS: A PREDICTIVE MODEL

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ABSTRACT
Coronary artery disease (CAD), which is characterized by the presence of coronary artery stenosis, is the frequent cause of death worldwide. The aim of this study was to assess hemodynamic effect due to the presence of non critical coronary stenoses. The computational fluid dynamics (CFD) was used to carry out numerical simulations, investigating the hemodynamic parameters. Twenty-four stenotic coronary arteries, with different non-significant stenosis severities, were reconstructed from frames of coronary angiographies of patients. The results show the distribution of the wall shear stress (WSS) in coronary vessels, and will be used to develop a predictive model to obtain shear stress value knowing stenosis area and length.
These models demonstrate that the assessment of WSS parameters may be useful to further refine risk stratification of patients having not clinically significant coronary artery stenosis.

Keywords: stenosis, computational fluid dynamics (CFD), wall shear stress (WSS), predictive models

1. INTRODUCTION

Coronary artery disease (CAD) is the most widely recognized cause of death. The number of deaths due to CAD has substantially increased between 1990 and 2013, rising from 5.74 million (12%) deaths to 8.14 million deaths (16.8%) (Nagavi 2015).
In 2015, 281,364 coronary angiography exams were performed in Italy, and during about the 50% of these examinations some revascularization procedures were needed. (Berti 2015)
Two main features of coronary stenosis are: the reduction of the section (i.e. the caliber of the lumen of the vessel) and the reduction of the diameter in the longitudinal direction (Falk 1995).
A stenosis is defined as hemodynamically significant when it reduces the diameter of a coronary vessel for at least 50% (Chang 2000).
Numerous trials have shown that the majority of coronary thromboses occurs on a non-obstructive plaque and often from plaques with mild stenosis (Pavone 2008).
Indeed, myocardial infarction is often the result of the rupture of a vulnerable plaque that does not determine any reduction of the coronary lumen (Pavone 2008).
Through some techniques, such as computational fluid dynamics (CFD), it is possible to solve basic equations that model the flow movement in different conditions and to calculate not easily accessible parameters in silico (Mazzitelli 2016).
Many advantages of CFD reside in the possibility to analyze different problems in different conditions. The level of detail is practically unlimited and repeatable (Steinman 2002).
Therefore, a study of the WSS focused on the onset of a coronary plaque and on plaque vulnerability can provide useful information to stratify patients at risk of adverse events (Eshtehardi 2016).
For this reason, many studies have been conducted by CFD analysis to investigate the hemodynamic variables involved in presence of stenosis of the coronary arteries (Caruso 2015).
Many authors have focused their analysis only on significant stenosis, consequently a detailed analysis of what happens in the presence of not significant stenosis is needed (Chaicana 2012) (Chaicana 2014) (Papadopoulos 2016).
The present study was conducted by including patients with non-significant stenosis for the purpose of evaluating changes of the hemodynamic parameters for different degrees of stenosis with the aim of developing a predictive model. The purpose of the model is to make a prediction of the WSS value by knowing the percentage area and stenosis length to support decisions in the medical-clinical setting.

2. MATERIAL AND METHODS

In this study, a cohort of 24 patients was considered.
All of the patients had a hemodynamically non-significant stenosis.

2.1 Geometry Reconstruction

For each coronary vessel, the geometry was reconstructed starting from a series of angiograms acquired during standard x-ray angiographies. The angiographic frame corresponding to the end of the diastole was selected to avoid any impact of systole on vessel geometry.

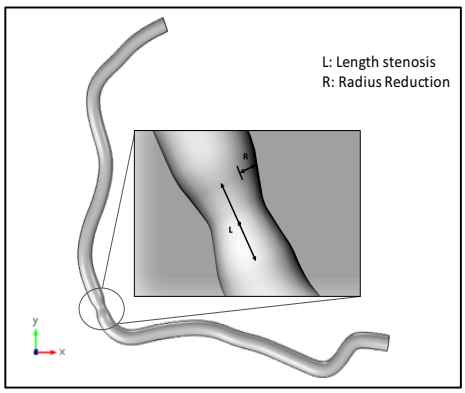


Figure 1: Coronary artery reconstruction

Geometry models were reconstructed using RHINOCEROS v.4.0 software (Robert McNeel & Associates, Seattle, WA, USA).
Figure 1 shows the geometrical model considered: the coronary of each patient incorporates the proximal section, the central section with stenoses and the distal one. It is consider in this study stenosis appeared on the main branch, as for all patients.
The evaluation of the stenosis percentage is obtained from the ratio between the minimum diameter of the lumen at the narrowest point level of the lesion and the reference diameter, which is the average of the lumen diameters in the reference segments upstream and downstream from the stenosis, judged as apparently healthy (Falk 1995).
From these parameters the percentage of the stenosis area was calculated as the ratio between the area of the healthy vessel ($Area_n$) and the area in the presence of stenosis ($Area_s$):

$$Area\% = \frac{Area_s}{Area_n} \cdot 100 \quad (1)$$

The length of stenosis for each patient was considered.

2.2 CFD Analysis

The software used to perform the simulations was COMSOL Multiphysics 5.2 (COMSOL Inc., Stockholm, Sweden). In the study, the blood was assumed as Newtonian with a density of 1.050 $[Kg/m^3]$ and viscosity of 0.0045 $[Pa \cdot s]$ (Stalder 2011).
The flow was considered as laminar, and 3D Navier-Stokes equations were used as governing laws (Gramigna 2015).
The incompressible condition gives:

$$\nabla . u = 0 \quad (2)$$

The governing equation used to solve the laminar model is:

$$\rho \frac{\delta u}{\delta t} + \rho(u.\nabla)\mathrm{u} = \nabla.\{-pI + \mu[\nabla \mathrm{u} + (\nabla \mathrm{u})^T]\} \quad (3)$$

where ρ is the fluid density, u is the fluid velocity, p is the pressure, I is the unit diagonal matrix and μ is the viscosity (Caruso 2016).
For each patient, a time-dependent flow waveform was assumed as an inlet boundary condition and as an outlet condition a specific waveform pressure was applied for each patient. All data and images used are specific to each patient, acquired after obtaining informed consent.
The no-slip boundary condition was applied to the wall to assume that the fluid in contact with walls is zero velocity (Caruso 2017).
Then the domain was discretized with tetrahedral and prismatic element, as shown in Figure 2, with an amount of ~ 205,000 elements for each coronary artery model.

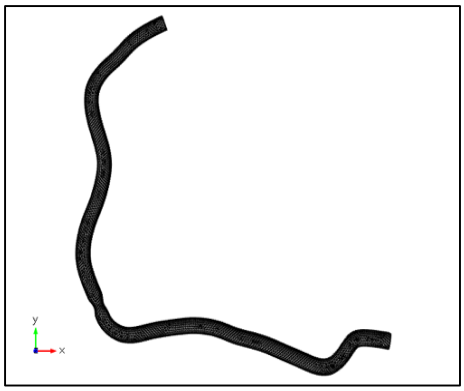


Figure 2: Coronary artery mesh

A comparison was made between two meshes. Table 1 shows the domain element statistics on the two mesh. For this geometry a finer mesh was chosen for better average element quality and a major number of elements.

Table 1: Finite Element Mesh

Domain Element Statistic		
Mesh Type	Finer	Fine
Number of elements	291662	80738
Average element quality	0,623	0,602
Mesh volume $[mm^3]$	1356	1342

Steady-state and transient CFD computations were performed; for the steady state and the time-dependent computation the PARDISO direct solver was used.
The index responsible for the change of morphology was calculated together with the orientation of the tissue that constitutes the wall of blood vessels: the wall shear stress (WSS) (Caruso 2015). That is defined by:

$$WSS = \sqrt{(\tau_x)^2 + (\tau_y)^2 + (\tau_z)^2} \quad (4)$$

where τ_x, τ_y, τ_z are the viscous stresses in x, y, z directions, respectively.
WSS values less than 1 N/m^2 mean the developing of plaque progression (Samady 2011).

WSS values greater than 3 N/m^2 are in the region of stenosis and involve clotting referred to the intimal thickness (Dolan 2014).

3. RESULTS

3.1. CFD RESULTS

The CFD results of 24 coronary arteries having a non-significant stenosis showed the distribution of the blood flow.

To represent the fluid dynamics within the 24 vessels under study, it was decided to show the results of the simulations of only one patients.

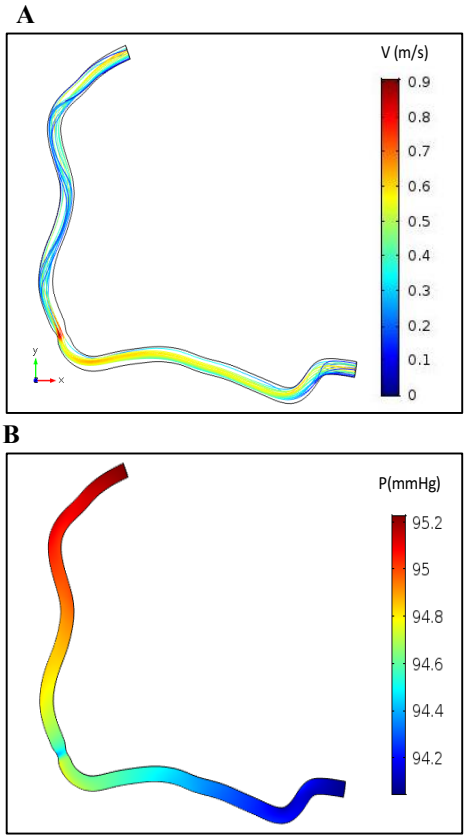


Figure 3: Coronary artery's A) velocity streamlines B) pressure

Figure 3A shows streamlines at the systolic peak to visually describe the fluid flow. The color expression in the streamlined plot indicates velocity magnitude (in $[m/s]$).

As shown in Figure 3A there is an increasing speed in correspondence to the lumen restriction where the maximum value of 0.9 $[m/s]$is reached.

Figure 3B shows the distribution of pressure; it is noted that the distal pressure due to the presence of the stenosis is less than the proximal pressure.

The WSS on the segment of stenosis was then calculated. Figure 4 shows the distribution of the WSS during the systolic peak in $[N/m^2]$. Its maximum value is reached along the stenosis of the coronary artery, that is, the maximum value occurs where there is a narrowing of the vessel due to the presence of stenosis and this value is 1.89 $[N/m^2]$.

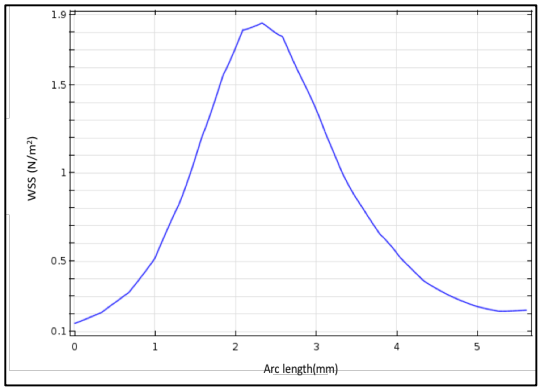


Figure 4: WSS value of the stenosis segment

The table 2 shows the overall results obtained from the CFD analysis of 24 patients. Patients were grouped into subgroups of 4 based on the percentage reduction of area due to stenosis. For each subgroup the mean length of the stenosis segment and the mean WSS was reported.

Table 2: Mean of results for 24 patients

	Range of Reduction Area [%]	Length Stenosis [mm]	WSS [Pa]
Group A	[2,11]	1,16	0,85
Group B	[12,22]	1,55	2,15
Group C	[23,34]	1,74	3,47
Group D	[36,60]	1,95	4,75

3.2. PREDICTION MODEL

For each patient, the data of the stenosis area - in percentage - and of the length of the stenosis have been reported.

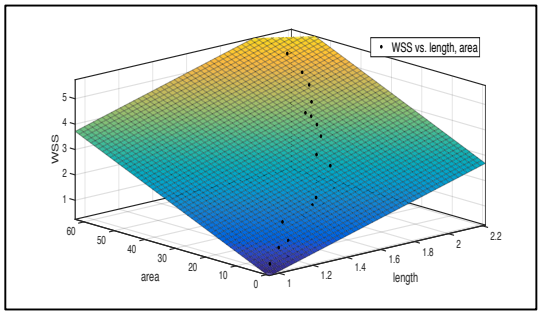
Furthermore, for each model of coronary artery the average values of the wall shear stress calculated on a surface of 2 mm length above and below the central point of stenosis are reported.

The data were used to perform the fitting curves and obtain the surfaces shows in Figure 5A. A first degree polynomial function was applies:

$$WSS = -1.554 + 1.931\ length + 0.05484\ area \quad (5)$$

where the coefficients have 95% confidence bounds and R-square goodness of the fit is 0.9094.

A



B

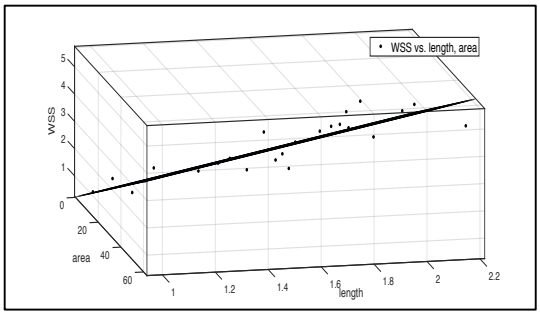


Figure 5: Model Prediction WSS vs Area, Length A) surface B) interpolation line

4. DISCUSSION

CFD analyses were performed in order to obtain the numerical results affecting blood velocity and shear stress on the wall, starting from Finite Elements of coronaries reconstructed geometries.

The flow generated by the coronary models, as shown in Figure 3, has an asymmetrical distribution of velocity streamlines, tangent lines to the instantaneous velocity vectors of the flow, toward the stenosis. The blood flow reaches the maximum velocity value during systole, at time t = 0.575 sec.

This value, as shown in Figure 3, is equal to 0.9 $[m/s]$ and occurs in correspondence to the narrowing of the vessel. As the degree of stenosis increases, i.e. the narrowing of the lumen of the vessel increases, the velocity increases. A high value of blood velocity downstream of the stenosis may cause turbulence phenomena. A raise of the velocity increases the tendency of red blood cells to accumulate in the axial laminae.

Wall shear stress (WSS) was finally analyzed. WSS assumes higher values where there is a narrowing of the vessel, and for the case of Figure 4 the maximum value is 1.89$[N/m^2]$.

Although, only in presence of significant stenosis, WSS reaches values of above 3 $[N/m^2]$ in the region of stenosis, involving clotting referred to the intimal thickness (Dolan 2014).

In these areas, a chronic high WSS value not only stimulates adaptative outward remodeling but also contributes to the saccular formation and atherosclerotic plaque destabilization (Soulis 2004).

On the contrary, in some regions both upstream and downstream of the stenosis, a low WSS value results, and there may be oscillation of WSS and stagnation of fluid, inducing perturbed endothelial alignment (Samady 2011).

Therefore investigating this parameter could provide additional information about the development of atherosclerosis in the vessel. For this purpose the prediction model has been created, in order to provide a forecast of the wall shear stress mean value starting from the area percentage and from the length of stenosis.

Figure 5A shows the surface at different variations of color gradation, from areas with low values of WSS in blue to areas with high values in red. If the percentage of stenosis and the length of the stenotic tract increase, there is an increase of the wall shear stress.

In fact, as it can be seen in Figure 5A, for the critical areas and the critical lengths the average value of WSS increases and becomes greater than 3 $[N/m^2]$.

Therefore that might be a useful indicator in order to stratify patients who, even if only treated with drug therapy, may undergo adverse events at follow-up.

5. CONCLUSION

This study showed that the inclusion of additional information on stenosis geometry allows a better stratification of patient's clinical risk, encompassing the predicted impact of flow parameters, such as the WSS despite the stenosis is non-significant.

To this purpose, the prediction of the wall shear stress can be useful to provide additional information about the progression of atherosclerotic plaque and endothelial damage and, consequently about the evolution of the disease.

6. LIMITATION AND FUTURE DIRECTIONS

A number of simplifying assumption were made to build up the model.

The first limitation of the study concerns the following simplifying assumption of rigid walls. Actually the blood vessels are distensible, since the area of the section of the vessel may changes as a function of vessel pressure. The second limitation is that blood is assumed as Newtonian. In presence of shear rate >100/s the assumption is generally accepted the assumption but in smaller vessels it is necessary to consider the non-Newtonian effect (Formaggia 2009). Next steps, through the use of specific sensors, will be needed to validate the data.

Further studies are needed to investigate coronary arteries in presence of hemodynamically significant stenosis to implement a more detailed prediction model.

REFERENCES

Berti S., Piccaluga E., Marchese A., Varbella F., Sardella G., Danzi G. B., and Magro B. 2015. Documento di posizione SICI-GISE sugli standard e linee guida per i laboratori di diagnostica e

interventistica cardiovascolare. Giornale Italiano di Cardiologia, 16(10), 590-600.

Caruso M. V., De Rosa S., Indolfi C., and Fragomeni G. 2015. Computational analysis of stenosis geometry effects on right coronary hemodynamics. In Engineering in Medicine and Biology Society (EMBC), 2015 37th Annual International Conference of the IEEE (pp. 981-984). IEEE.

Caruso M. V., Gramigna V., Renzulli A., and Fragomeni, G. 2016. Computational analysis of aortic hemodynamics during total and partial extra-corporeal membrane oxygenation and intra-aortic balloon pump support. Acta of Bioengineering and Biomechanics, 18(3), 3-9.

Caruso M. V., Renzulli A., and Fragomeni G. 2017. Influence of IABP-Induced Abdominal Occlusions on Aortic Hemodynamics: A Patient-Specific Computational Evaluation. ASAIO Journal, *63*(2), 161-167.

Chaichana T., Sun Z., and Jewkes J. 2012. Computational fluid dynamics analysis of the effect of plaques in the left coronary artery. Computational and mathematical methods in medicine, 2012.

Chaichana T., Sun Z., and Jewkes J. 2013. Hemodynamic impacts of left coronary stenosis: A patient-specific analysis. Acta of bioengineering and biomechanics, 15(3).

Chang J. B., Prasad K., and Olsen E. R. 2000. Textbook of angiology. Springer.

Creager M. A., Beckman J. A., and Loscalzo J. 2012. Vascular medicine: a companion to Braunwald's heart disease. Elsevier Health Sciences.

Dolan J. M., Kolega J., and Meng H. 2013. High wall shear stress and spatial gradients in vascular pathology: a review. Annals of biomedical engineering, 41(7), 1411-1427.

Eshtehardi P., and Teng, Z. 2016. Protective or destructive: High wall shear stress and atherosclerosis. Atherosclerosis, *251*, 501-503.

Falk, E., Shah, P. K., and Fuster, V. 1995. Coronary plaque disruption. Circulation, 92(3), 657-671.

Formaggia, L., Quarteroni, A., and Veneziani, A. (Eds.). 2010. Cardiovascular Mathematics: Modeling and simulation of the circulatory system (Vol. 1). Springer Science & Business Media.

Gramigna V., Caruso M. V., Rossi M., Serraino G. F., Renzulli A., and Fragomeni G. 2015. A numerical analysis of the aortic blood flow pattern during pulsed cardiopulmonary bypass. Computer methods in biomechanics and biomedical engineering, 18(14), 1574-1581.

Mazzitelli R., Boyle F., Murphy E., Renzulli A., and Fragomeni G. 2016. Numerical prediction of the effect of aortic Left Ventricular Assist Device outflow-graft anastomosis location. Biocybernetics and Biomedical Engineering, 36(2), 327-343.

Naghavi M., Wang H., Lozano R., Davis A., Liang X., Zhou M., and Aziz, M. I. A. 2015. Global, regional, and national age-sex specific all-cause and cause-specific mortality for 240 causes of death, 1990-2013: a systematic analysis for the Global Burden of Disease Study 2013. Lancet, 385(9963), 117-171.

Papadopoulos K. P., Gavaises M., Pantos I., Katritsis D. G., and Mitroglou N. 2016. Derivation of flow related risk indices for stenosed left anterior descending coronary arteries with the use of computer simulations. Medical Engineering & Physics, 38(9), 929-939.

Samady H., Eshtehardi P., McDaniel M. C., Suo J., Dhawan S. S., Maynard C., and Giddens, D. P. 2011. Coronary artery wall shear stress is associated with progression and transformation of atherosclerotic plaque and arterial remodeling in patients with coronary artery disease. Circulation, CIRCULATIONAHA-111.

Soulis J. V., Farmakis T. M., Giannoglou G. D., and Louridas G. E. 2006. Wall shear stress in normal left coronary artery tree. Journal of biomechanics, 39(4), 742-749.

Stalder A. F., Liu Z., Hennig J., Korvink J. G., Li K. C., and Markl M. 2011. Patient specific hemodynamics: combined 4D flow-sensitive MRI and CFD. In Computational Biomechanics for Medicine (pp. 27-38). Springer New York.

Steinman D. A. 2002. Image-based computational fluid dynamics modeling in realistic arterial geometries. Annals of biomedical engineering, 30(4), 483-497.

HEMODYNAMIC COMPARISON OF THIN VS STANDARD INTRA-AORTIC BALLOON USING A PATIENT-SPECIFIC CFD MODELING

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ABSTRACT

Intra-aortic balloon pump -IABP- is a mechanical cardiocirculatory support used to treat patients with cardiovascular diseases. Balloon volume influences both the standard therapy, since it is correlated to some clinical complications, and the weaning from the assistance, since one approach is the volume-based reduction.

The aim of this study was to investigate the influence of balloon volume on hemodynamics, evaluating the perfusion of the four main districts by comparing two volumes (standard and thin). Computational fluid dynamic - CFD - simulations were performed in a patient-specific aorta model. Balloons were numerically reproduced with their inflation-deflation behaviors.

The results highlighted how size influences the hemodynamics, generating a decrease of perfusion in head and arms and a hyperperfusion in visceral vessels and in legs when adopting a thin volume compared with the standard one. This computational comparison demonstrated that a reduced-volume balloon is healthier, since it produces a better hemodynamic profile.

Keywords: intra-aortic balloon pump, computational fluid dynamics, hemodynamics, simulations

1. INTRODUCTION

Intra-aortic counterpulsation is used to treat patients with different cardiovascular diseases, such as cardiogenic shock, myocardial infarction, etc. (Krishna and Zacharowski 2009), generating different beneficial effects, like the augmentation of diastolic aortic pressure and the increase of coronary perfusion (Papaioannou and Stefanadis 2005).

This mechanical support consists of two major components (Krishna and Zacharowski 2009): a catheter, with a balloon connected to its distal end, and a console, which shuttles helium through the catheter lumen in order to inflate and deflate the balloon with opposite trend respect to the cardiac cycle, thus obtaining a counterpulsating pump (Trost and Hillis 2006). Indeed, it is also known as intra-aortic balloon pump -IABP-.

In daily practice, Maquet/Datascope IABPs (MAQUET Cardiovascular, New York, United States) are widely used devices for the counterpulsation treatment. According to its guidelines, the balloon must be placed in the descending aorta, with its tip 2 or 3 cm distal to the origin the left subclavian artery -LSA- (Krishna and Zacharowski 2009) and before the iliac bifurcation. Moreover, balloon volume must be chosen according to the patient's height (Krishna and Zacharowski 2009).

For a fully cardiocirculatory assistance, an assist ratio of 1:1 is generally adopted (Gelsomino et al. 2012), whereas, for the counterpulsation weaning, two methods are available: frequency-reduction and volume-reduction (Lewis and Courtney 2006). Actually, there are very few studies that compare these two approaches in order to identify the best method. A preliminary investigation was performed by Lewis and Courtney (2006), who reviewed literature. They concluded that the volume-reduction was the most effective weaning approach. Recently, the same result was reached by Gelsomino et al. (2016 a) with an *in-vivo* comparison in a cohort of twelve pigs.

In addition, different clinical complications, such as bleeding, thromboembolism, distal leg ischemia, or hypoperfusion of visceral organs can occur, which are related to malpositioning, to a too long balloon or to a wrong balloon size.

El-Halawany et al. (2015) present a case of patient who suffered from bowel ischemia as a result of a malpositioned IABP. Also Vondran et al. (2016) investigate the impact of a low balloon position on visceral perfusion in an *in-vivo* animal model, reporting that the positioning is critical for obtaining a satisfactory outcome. Similar results were obtained by Siriwardena et al. (2015).

A recent research compares a 35 mL short balloon with a 40 mL standard size balloon (Gelsomino et al. 2016 b). Authors conclude that the short IAB is as effective as the standard one in supporting hemodynamics and coronary circulation. Since the two analyzed balloons have different lengths, the results are related both to volume and to length variations.

The influence of length was investigated by (Gelsomino et al. 2016 c) considering a short and a normal 40 mL balloon, highlighting that the short balloon is advantageous to prevent visceral occlusions and it is beneficial cardiac and coronary-related effects.

Finally, the same authors evaluate the influence of balloon size and volume on mesenteric and renal flows considering a short 35-mL IABP, a short 40-mL IABP, a long 35-mL IABP and a long 40-mL IABP (Gelsomino et al. 2017).
For these reasons and since there are no numerical investigations that analyze the effects of balloon volume/size on aortic hemodynamics, the purpose of this study was to assess the influence of IAB size on flow in aorta, evaluating the perfusion ratio on vascular districts (head, arms, abdomen and legs) comparing two balloon volumes (standard and thin) with the same length. Computational fluid dynamics -CFD- was chosen to perform this analysis, since this method presents different advantages, as illustrated in our previous work (Caruso et al. 2017).

2. MATERIALS AND METHODS

2.1. Aorta model

The physiological model of aorta was reconstructed from Dicom images of computerized tomography -CT- scan of a 56-year-old woman (158 cm tall), performed for clinical reasons. The sequence of images included 512, 416 and 90 slices in axial plane, sagittal plane, and coronal plane, respectively, with an in-plane resolution of 0.9375 × 0.9375 mm and a slice thickness of 1.2 mm. The written informed consent of the patient was obtained to use these images in the study.
The 3D virtual model of aorta and of its vessels was obtained by applying the segmentation approach using the open source software Invesalius (de Moraes et al. 2011). Since it provides a STL file, in order to obtain a 3D solid model exploitable for CFD simulations, different reverse engineering techniques (Pham and Hieu 2008) were applied.
The final model included the ascending and the descending trunks and ended with the iliac bifurcation. Also the supra-aortic and the visceral/abdominal vessels were reported (Table 1 and Figure 1).

Table 1: Aorta vessels

Acronym	Name	District
RSA	right subclavian artery	arms
RCA	right carotid artery	head
LCA	left carotid artery	head
LSA	left subclavian artery	arms
SMA	superior mesenteric artery	abdomen
CT	celiac trunk	abdomen
IMA	inferior mesenteric artery	abdomen
RRA	right renal artery	abdomen
LRA	left renal artery	abdomen
RIA	right iliac artery	legs
LIA	left iliac artery	legs

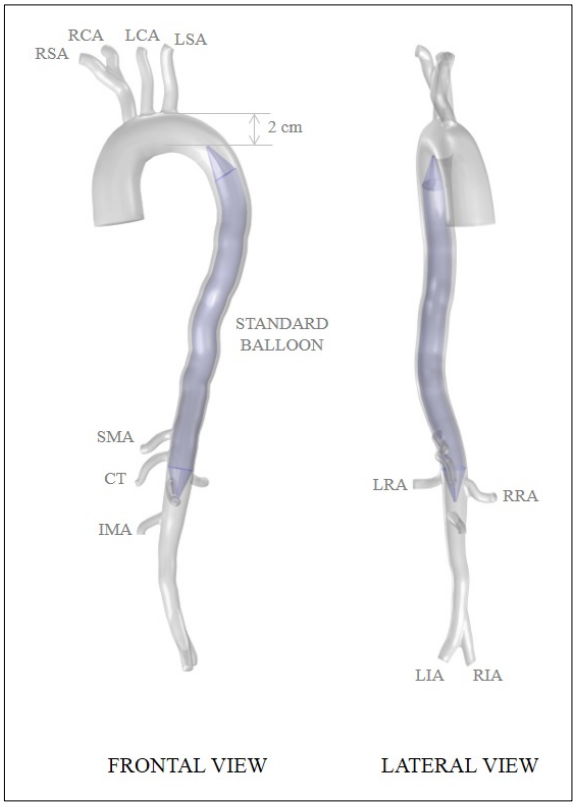

Figure 1: Aorta and standard IAB (34 cm^3) models in frontal and lateral views

2.2. Balloon selection and modeling

Even if technical guidelines indicate that the balloon must be selected considering the patient's height (Trost and Hillis 2006), different studies reported that the distance between left subclavian artery -LSA- and the celiac trunk -CT- is the best selection criterion (Rastan et al. 2010, Tapia et al. 2015, Parissis et al. 2011, Sukhodolya et al. 2013), as it reduces clinical complications. For this reason, the Linear 7.5 Fr with 34 cm^3 (fully inflated caliber of 15 mm) was chosen for full assistance and considered as standard balloon. A balloon of 30 cm^3 was supposed with the aim of considering a lower volume and, therefore, a smaller size. Assuming the same length of 221 mm, this thin-balloon had a fully inflated caliber of 14 mm.
The two 3D balloons were placed in the descending aorta with a distance of 2 cm from LSA emergence (Figure 1), as suggested by Caruso et al. (2017). The 1:1 assist ratio was considered for both assistance cases. The inflation/deflation behaviors were numerically reproduced with parametric studies, in which balloon radius changes according to the cardiac cycle with 8 degree Fourier functions (Figure 2). A cardiac cycle of 1s was set.

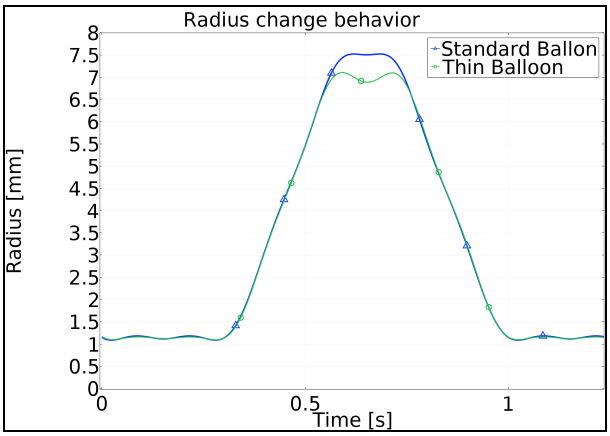

Figure 2: Radius change behavior for the standard and the thin balloons

2.3. CFD modeling

Since the aorta is a large vessel, blood can be approximated as a Newtonian and incompressible fluid, with a density of 1,060 kg/m^3 and a viscosity of 0.0035 Pa·s (Caruso et al. 2016). Moreover, the flow can be numerically described by means of 3D Navier-Stokes equations (Gramigna et al. 2015). As boundary condition, the same mean inlet flow of about 5 L/min was applied in the two cases, whereas zero-pressure conditions were set as outlets in all vessels, as in similar comparative studies (Caruso et al. 2017, Karmonik et al. 2012).

Since information regarding the effects of counterpulsation on aorta wall elasticity is unavailable (Lawford et al., 2008), all aorta walls were modelled as rigid surfaces and the no-slip boundary condition was imposed in both assistance cases. The same approximation is generally chosen in comparative analyses (Caruso et al. 2016, Gramigna et al. 2015, Karmonik et al. 2012).

The CFD simulations were carried out using COMSOL 5.2 (COMSOL Inc, Stockholm, Sweden). Since parametric studies are very expensive, in order to ensure a good compromise between accuracy and computational costs (Caruso et al. 2017), the meshes had four boundary layers and tetrahedral elements, with a changeable total number of elements according to the cardiac cycle, as illustrated in Table 2.

The Pardiso solver was employed to solve the Navier-Stokes equations, choosing the P1-P1 discretization and a step of 0.001.

Table 2: Mesh details: total number of elements

Balloon	Fully inflation	Fully deflation
Standard	466,806	1,382,321
Thin	499,615	1,358,654

3. RESULTS

Flow distribution waveform in each district of human body during counterpulsation with standard balloon and with thin balloon is reported in Figure 3. In both cases, the flow followed the balloon inflation/deflation behavior, with the same trend in the head and arms and with an opposite trend in the abdomen and in the legs. Moreover, comparing the standard counterpulsation with those obtained with a thin balloon, a reduction of perfusion occurred in the supra-aortic vessels, whereas the visceral and the iliac flows increased. These changes in the hemodynamics produced a decrease in the mean perfusion of head and arms and an increment of flow in the abdominal vessels and so in the abdominal organs and in the legs, as illustrated in Figure 4.

In detail, the use of thin balloon created a reduction of about 1.36% and 1.51 % in the cerebral and in the arms flow rates, respectively, and an increase of about 1.59% and 3.40 % in the visceral and legs perfusion, as reported in Table 3. Thus, the volume reduction of about 13% generates changes in the hemodynamics in aorta for a mean flow value of about 2%.

Moreover, to better understand the influence of thin balloon on hemodynamics, the wall shear stress -WSS-, which is the friction force created by blood motion on vessel walls, was evaluated according to equation reported in Caruso et al. (2015). Since this mechanical indicator is time-dependent, it was estimated when the balloon was fully-inflated (t=0.65 s) in order to compare the effects of the two volumes on aorta walls, as reported in Figure 5.

The physiological level of WSS is about 1.5-2.0 Pa, as reported by Malek et al. (1999), whereas values less than 0.481 Pa are considered as low and correlated to atherosclerotic place formation (Lee et al. 2008). For this reason, a color scale with a maximum value of 0.5 Pa was set in Figure 5, in order to identify the areas characterized by very low WSS.

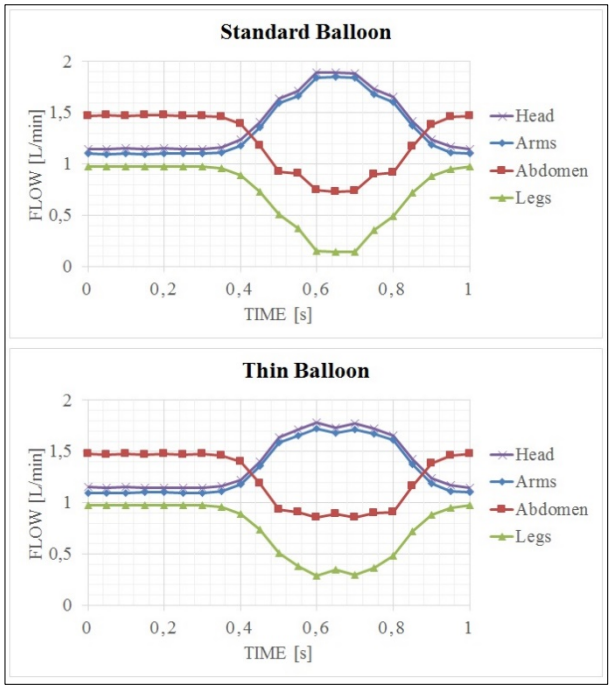

Figure 3: Flow distribution waveform in each district in case of standard counterpulsation and in case of support with thin balloon

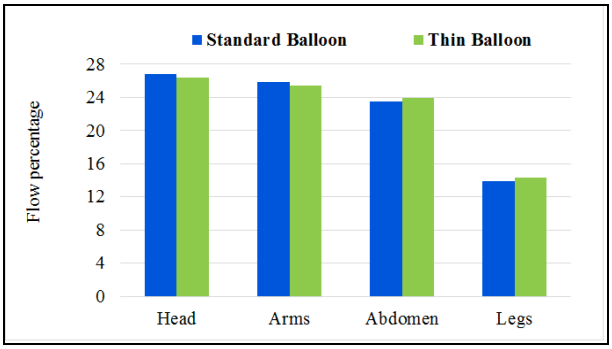

Figure 4: Mean flow percentage distribution in each district in case of standard counterpulsation and in case of thin balloon, evaluated respect to the inlet flow

Table 3: Comparison between standard and thin balloon in terms of volume and flow rates. Note: the perfusion of standard balloon is expressed respect to the inlet flow, whereas the flow rate of thin balloon is evaluated respect to the standard balloon perfusions

Balloon	Standard	Thin
Volume [cm^3]	34	30
Head perfusion	26.77 %	- 1.36 %
Arms perfusion	25.83 %	- 1.51 %
Abdomen perfusion	23.54 %	+ 1.59 %
Legs perfusion	13.86 %	+ 3.40 %

The aorta surface before and around the fully-inflated balloon had the same WSS distribution in case of both standard and thin balloons. In detail, the supra-aortic vessels were subjected to high WSS (>0.5 Pa), whereas the surface around the balloon presented a very low value (≈ 0 Pa). The significant difference between the two balloons occurred below them. Indeed, the WSS in the final part of abdominal aorta was about 0 Pa in case of standard balloon and of about 0.3 Pa in case of thin balloon. Also the renal arteries, the IMA and the iliac bifurcation presented higher WSS values in case of thin balloon.

4. DISCUSSION

Intra-aortic counterpulsation is the gold standard treatment for different cardiovascular diseases (Trost and Hillis 2006, Krishna and Zacharowski 2009). Balloon size has a key role in this cardiocirculatory assistance. Indeed, it influences both clinical benefits (Trost and Hillis 2006) and complications (Rastan et al. 2010, Tapia et al. 2015, Parissis et al. 2011, Sukhodolya et al. 2013). In addition, the volume-based reduction is a methodology available for the counterpulsation weaning (Lewis and Courtney 2006). For these reasons, the standard counterpulsation and the treatment performed with a thin balloon were compared, using computational simulations carried out in a patient-specific aorta model in order to investigate the influence of IAB size on hemodynamics.

As expected, flow waveforms follow the balloon inflation-deflation behavior, with the same trend for head and arms and an opposite trend for abdominal organs and legs. This was due to the presence of balloon in the descending aorta that obstructed it, creating a hyperperfusion in the vessels above it (same trend) and a hypoperfusion in the trunks below it (opposite trend) (Figure 3). Indeed, different studies demonstrated how IABP improved cerebral blood flow (CBF), such as the research of Pfluecke et al. (2014).

Moreover, flow results highlighted how the thin balloon reduced the head and arms perfusions and intensified the flow in abdominal organs and legs. This founding is in agreement with a recent study whose authors indirectly compared two IAB sizes (Caruso et al. 2017) and with the research of Byon et al. (2011). Similar results were also obtained in an *in-vitro* investigation (Biglino et al. 2008). Thus, this assessment was validated.

The analysis of flow rates demonstrated how the thin balloon is better to prevent the occlusion of visceral vessels and the hypoperfusion of legs, since the hemodynamics had a better performance of about 2% as a volume reduction of about 13% was performed (Table 3).

A recent study evaluated the influence of balloon size and volume on mesenteric and renal flows considering a short 35-mL IABP, a short 40-mL IABP, a long 35-mL IABP and a long 40-mL IABP (Gelsomino et al. 2017). Since our analysis considered two balloons with different volume and size (34 cm3 and 15 mm and 30 cm3 and 14 mm respectively) and the same length of 221 mm, there is an analogy between it and the comparison of two long balloons performed by (Gelsomino et al. 2017). Our increase of about 1.6 % of abdominal perfusion in case of thin balloon (Table 3) is in agreement with their data. Indeed, they indicated that the smaller IAB generates a better visceral flow rate, even if they consider this difference not significant.

Since distal leg ischemia and hypoperfusion-obstruction of abdominal organs are the most frequent complications of IABP treatment (Tapia et al. 2015), we believe that even a little improvement can be important to achieve a better hemodynamic profile.

The WSS investigation revealed that the standard balloon generated stagnant areas (WSS≈ 0 Pa) in the descending aorta below the balloon, creating stasis in this trunk segment and in the iliac arteries (Figure 5), whereas, in case of thin balloon, WSS was about 0.3 Pa. WSS is highly correlated to the atherosclerosis (Malek et al. 1999). Thus, the worst situation occurred in case of standard balloon. As a result, thromboembolic events could happen, which are another diffused disease after counterpulsation treatment (Tapia et al. 2015).

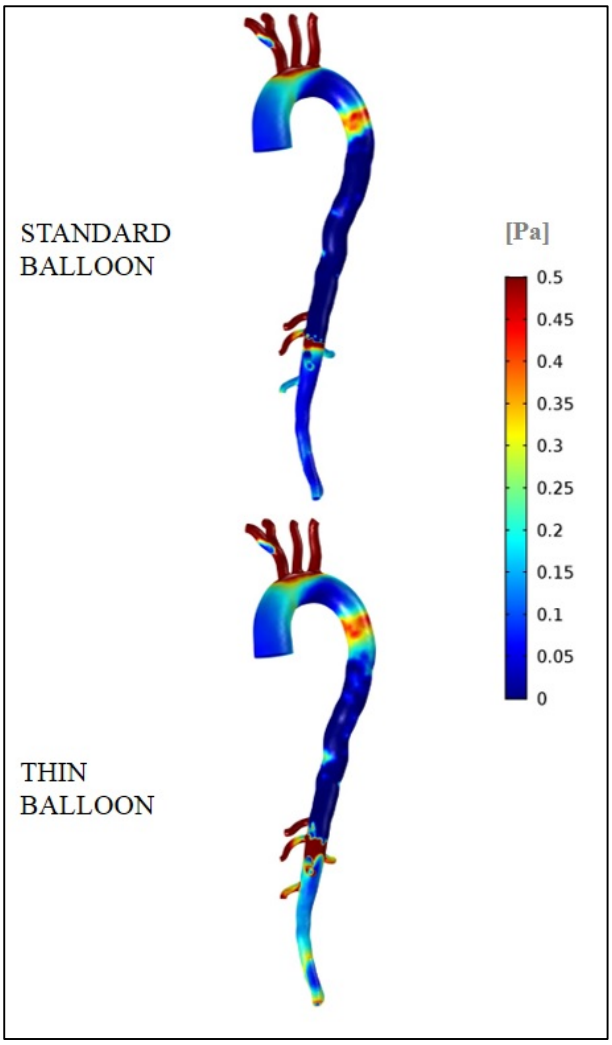

Figure 5: WSS evaluated during the fully inflation (t=0,65 s) in case of standard counterpulsation and in case of support with thin balloon. Note: the color scale was set with a maximum of 0.5 Pa in order to visualize the areas with very low values

5. CONCLUSION

This computational investigation compared the standard balloon used for the counterpulsation treatment and a thin balloon in a patient-specific model in order to investigate the influence of IAB size on hemodynamics. Significant changes were reported, both in terms of flow and WSS, indicating that a thin balloon is a better choice for reducing clinical complications when compared to those suggested by actual guidelines. As a result, a smaller volume could be adopted both during treatment and for the weaning, thus improving the patient's outcome.

ACKNOWLEDGMENTS

This research is part of the project "Computational Assessment of Hemodynamics in Presence of Intra-aortic Balloon Pump," realized in collaboration with Prof. Renzulli. The authors wish to dedicate this paper to his memory.

REFERENCES

Caruso M.V., Gramigna V., Rossi M., Serraino G.F., Renzulli A., Fragomeni G., 2015. A computational fluid dynamics comparison between different outflow graft anastomosis locations of Left Ventricular Assist Device (LVAD) in a patient-specific aortic model. Journal for numerical methods in biomedical engineering, 31(2), 1-12.

Caruso M.V., Gramigna V., Renzulli A., Fragomeni G., 2016. Computational analysis of aortic hemodynamics during total and partial extra-corporeal membrane oxygenation and intra-aortic balloon pump support. Acta of Bioengineering and Biomechanics, 18(3), 3-9.

Caruso M.V., Renzulli A., Fragomeni G., 2017. Influence of IABP-Induced Abdominal Occlusions on Aortic Hemodynamics: A Patient-Specific Computational Evaluation. ASAIO Journal, 63(2), 161-167.

de Moraes T.F., Amorim P.H., Azevedo F.S., da Silva J.V., 2011. InVesalius: An open-source imaging application. Computational Vision and Medical Image Processing: VipIMAGE 2011, 405.

El-Halawany H., Bajwa A., Shobassy M., Qureini A., Chhabra R., 2015. Ischemic colitis caused by intra-aortic balloon pump counterpulsation. Case reports in gastrointestinal medicine, 2015.

Gelsomino S., Lozekoot P.W., de Jong M.M., Lucà F., Parise O., Matteucci F., ... Maessen J.G., 2017. Is visceral flow during intra-aortic balloon pumping size or volume dependent?. Perfusion, 32(4), 285-295.

Gelsomino S., Lozekoot P.W., Lorusso R., De Jong M.J., Parise O., Matteucci F., ... La Meir M., 2016 a. The Optimal Weaning Strategy for Intraaortic Balloon Counterpulsation: Volume-Based Versus Rate-Based Approach in an Animal Model. The Annals of thoracic surgery, 101(4), 1485-1493.

Gelsomino S., Lozekoot P.W., Lorusso R., De Jong M.M., Parise O., Matteucci F., ... Gensini G.F., 2016 b. A New 35-mm Short Intra-aortic Balloon Catheter: A Suitable Option Also for Non–Small-Sized Patients?. Innovations: Technology and Techniques in Cardiothoracic and Vascular Surgery, 11(1), 46-53.

Gelsomino S., Lozekoot P.W., Lorusso R., de Jong, M.M., Parise O., Matteucci F., ... Maessen J.G. 2016 c. Comparing short versus standard-length balloon for intra-aortic counterpulsation: results from a porcine model of myocardial ischaemia–reperfusion. European Journal of Cardio-Thoracic Surgery, 49(5), 1361-1369.

Gelsomino S., Renzulli A., Rubino A.S., Romano S.M., Lucà F., Valente S., ... Lorusso R., 2012. Effects of 1: 1, 1: 2 or 1: 3 intra-aortic balloon counterpulsation/heart support on coronary haemodynamics and cardiac contractile efficiency in an animal model of myocardial ischaemia/reperfusion. European Journal of Cardio-Thoracic Surgery, ezr327.

Gramigna V., Caruso M.V., Rossi M., Serraino G.F., Renzulli A., Fragomeni G., 2015. A numerical analysis of the aortic blood flow pattern during pulsed cardiopulmonary bypass. Computer methods in biomechanics and biomedical engineering, 18(14), 1574-1581.

Karmonik C., Partovi S., Loebe M., Schmack B., Ghodsizad A., Robbin M.R., ... Lumsden A.B., 2012. Influence of LVAD cannula outflow tract location on hemodynamics in the ascending aorta: a patient-specific computational fluid dynamics approach. ASAIO Journal, 58(6), 562-567.

Krishna M. and Zacharowski K., 2009. Principles of intra-aortic balloon pump counterpulsation. Continuing Education in Anaesthesia, Critical Care & Pain, 9(1), 24-28.

Lawford P.V., Ventikos Y., Khir A.W., Atherton M., Evans D., Hose, D.R., ... Hollis A.P., 2008. Modelling the interaction of haemodynamics and the artery wall: current status and future prospects. Biomedicine & Pharmacotherapy, 62(8), 530-535.

Lee S.W., Antiga L., Spence J.D., Steinman D.A., 2008. Geometry of the carotid bifurcation predicts its exposure to disturbed flow. Stroke, 39(8), 2341-2347.

Lewis P.A. and Courtney M.D., 2006. Weaning intraaortic balloon counterpulsation: the evidence. British Journal of Cardiac Nursing, 1(8), 385-389.

Malek A.M., Alper S.L., Izumo S., 1999. Hemodynamic shear stress and its role in atherosclerosis. Jama, 282(21), 2035-2042.

Papaioannou T.G. and Stefanadis C., 2005. Basic principles of the intraaortic balloon pump and mechanisms affecting its performance. ASAIO journal, 51(3), 296-300.

Parissis H., Soo A., Leotsinidis M., Dougenis D., 2011. A statistical model that predicts the length from the left subclavian artery to the celiac axis; towards accurate intra aortic balloon sizing. Journal of cardiothoracic surgery, 6(1), 95.

Pfluecke C., Christoph M., Kolschmann S., Tarnowski D., Forkmann M., Jellinghaus S., ... Ibrahim, K., 2014. Intra-aortic balloon pump (IABP) counterpulsation improves cerebral perfusion in patients with decreased left ventricular function. Perfusion, 29(6), 511-516.

Pham D.T. and Hieu L.C., 2008. Reverse engineering–hardware and software. Reverse Engineering, 33-70.

Rastan A.J., Tillmann E., Subramanian S., Lehmkuhl L., Funkat A.K., Leontyev S., ... Mohr F.W., 2010. Visceral arterial compromise during intra-aortic balloon counterpulsation therapy. Circulation, 122 (11 suppl 1), S92-S99.

Siriwardena M., Pilbrow A., Frampton C., MacDonald S.M., Wilkins G.T., Richards A.M., 2015. Complications of intra-aortic balloon pump use: does the final position of the IABP tip matter?. Anaesthesia & Intensive Care, 43(1).

Sukhodolya T., Damjanovic D., Beyersdorf F., Benk C., Heilmann C., Blanke P., ... Trummer G., 2013. Standard intra-aortic counterpulsation balloon may cause temporary occlusion of mesenterial and renal arteries. ASAIO Journal, 59(6), 593-599.

Tapia G.P., Zhu X., Liang P., Su G., Liu H., Li S., 2015. IABP ballooning in Chinese patients. Acta Medica 2: 79.

Trost J.C. and Hillis L.D., 2006. Intra-aortic balloon counterpulsation. The American journal of cardiology, 97(9), 1391-1398.

Vondran M., Rastan A.J., Tillmann E., Seeburger J., Schröter T., Dhein S., ... Mohr F.W., 2016. Intra-Aortic Balloon Pump Malposition Reduces Visceral Artery Perfusion in an Acute Animal Model. Artificial organs, 40(4), 334-340.

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ADAPTED ICP ALGORITHM FOR SURFACE BASED REGISTRATION IN IMAGE GUIDED SURGERY

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ABSTRACT

Image guided surgery has established in modern surgery rooms, enabling high technology support for complicated surgical interventions. The ability to exactly position surgical tools, even if the target of surgery is subsurface, relying just on pre-acquired image data, causes the great success of surgical navigation. In cerebral surgery, image guidance has a long tradition, even in orthopedics; recently it also appears to abdominal surgery.

A major prerequisite for accurate position navigation is the careful mutual registration of patient-, tracking- and imaging-domains. Only intuitive and precise handling of the registration procedure leads to satisfying results. An easy to use and accurate registration method, integrating the iterative closest point (ICP) algorithm was developed and implemented as showcase in a Matlab® based tracking environment.

Image data from a diagnostic scan are preprocessed by anisotropic diffusion filtering and reformatted to cubic voxels. The point sets for registration are extracted from the image volume and acquired by a tracked pointing device. Rough re-orientation of registration data is achieved by equalization of principal components. The ICP algorithm is applied to fully register both data sets. Accuracy of registration is quantified by distance-measurements of the transformed tracking points from the surface and by measuring the summed distance of physical landmarks on the object's surface. The registration yields accurate overlay of the tracking and patient image domains, allowing exact navigation of surgical tools. The easy handling and accuracy of the developed registration method manifests the specific potential for clinical application.

Keywords: image guided surgery, medical image processing, virtual reality, augmented reality

1. INTRODUCTION

The combination of modern computer visualization techniques, accurate diagnostic imaging techniques and further development of exact position tracking, facilitated advances in image guided surgery during the last three decades. Modern intra-operative navigation was inspired by frame-based stereotaxis; a technique using preoperative images for intra-operative guidance to exactly place needles, catheters or electrodes into intracranial structures. The challenge is to avoid collateral damage when accessing subsurface targets, thus preserving neural functionality. Careful preoperative planning helps minimizing craniotomy, resulting in less risk of surgery, shorter anesthesia, contributing to more successful rehabilitation.

These experiences gave rise to the development of frameless stereotaxis in the 1990s. For the first time the enormous potential of recently developed volume imaging modalities and real-time tracking of surgical instruments was combined. The integration of powerful computer based methods and graphics makes it a powerful tool in the surgery room (Enchyev 2009). Image guided navigation is divided into two phases, the non-realtime procedures outside the operating theatre (OT), e.g. radiological image acquisition, visualization and planning, and the real-time intra-operative phase during surgery. In a sterile and time critical environment registration, tool-tracking and intra-operative visualization is performed. These special requirements demand well designed hard- and software tools. The introduction of this modern methodology is highly beneficial for patient care and economical aspects of treatment (Paleologos et al. 2000).

The development of functional MRI further improves the method. Exact cortical localization of functional foci, e.g. the centers of motoric activities, speech, or visual perception, can be considered in the planning of the surgical aditus. This minimizes functional handicaps as a post-surgical manifestation (Nimsky et al. 2005).

During extensive brain surgery, a shift of brain tissue is observed, after opening of the hard meninx, the dura mater. For further exact localization of the tools these shift-related deviations are compensated either by intra-operative imaging or by computational assessment of offsets performing elastic modelling of preoperative

image (Hatiboglu et al. 2009, Liu et al. 2014, Reinbacher et al. 2014, Scheufler et al. 2011).
Orthopedic surgery offers a broad range of surgical navigation applications, ranging from hip and knee to spine surgery. The tasks comprise exact replacement of pathologic morphology, the positioning of artificial joints or screws and the use of surgical robots (Blackeny et al. 2011, Kelly and Swank 2009, Mason et al. 2007, Verdú-López et al. 2014).
Much research effort is done in the field of model based navigation. In contrast to the previously discussed image guided methods, a generic model of the surgical target is individually adopted to the patient, according to intra-operative measurements of control points. This needs no imaging modalities and prevents the patient from potential risk of radiation (Habor 2013).
Most recent and comprehensive research paradigm is the "digital OT". The navigation of information, i.e. the aggregation of all kind of information, from all available sources in Pictures Archiving and Communication System (PACS) and the Hospital Information System (HIS) is the basis for all treatment. Data are filtered and processed for intuitive representation in the OT. This "digital OT" is the high end development of the top system providers (Malarme et al. 2008).
Accurate registration is still an essential requirement for successful employment of navigation techniques. The intuitive and efficient handling of the registration procedure, i.e. the overlay of world coordinates (tracking system) and patient coordinates (image), is inevitable. Most applications rely on point to point registration. This requires fiducial landmarks, since inherent anatomical landmarks are mostly not reliable or easy to identify. In addition, the fixation of fiducial markers needs certain effort, e.g. a set of bone screws drilled into the skull, or some bulky equipment, like dental casts bonded to the patient's teeth (Bettschart et al. 2012, Morea et al. 2011, Aldana et al. 2010).
Alternatively surface-to-points registration is developed. Using surfaces, the inaccurate detection of fiducial markers is eliminated as a source of error. The mean distance of a surface, extracted from radiological images, and points on a respective surface, acquired in the patient domain, is minimized. Chamfer matching combined with steepest gradient optimization is used for registration of tracked tools and radiological images (Backfrieder et Zwettler 2014). Methods based on the ICP algorithm exist for intraoperative assessment of organ position and size (Benincasa et al. 2008) and a recent work describes a feasibility study to match radiological images and calibrated stereovision data (An et al. 2015). The latter approach allows no interaction with tracking tools.
In this work an ICP based surface-to-points registration is presented. A user friendly and robust integration of tool tracking in the image domain is realized in an experimental MATLAB ® based surgical navigation system.

2. MATERIAL

In this work a new robust and user friendly method for registration is presented. It takes advantage of inherent landmarks, thus the efforts for mounting and careful conservation will be obsolete, and even the registration procedure is straight forward. As an inherent landmark any externally accessible surface of the patient is proper. The registration algorithm is tested with a physical head phantom, a model of a vertebra manufactured by a 3D prototyping printer, and an x-ray scan of a human head.
Image volumes are acquired with a Siemens Cardiac Sensation 64 scanner, 220 slices with a 512x512 matrix, 16 bit per pixel, voxel-size 1x0.4x0.4mm^3. A three panel display of the physical head phantom is shown in Fig. 1. The skull bone is mimicked by plastics and the soft tissue parts, i.e. the brain, are modeled with rubber, the darker gray indicates the lower attenuation coefficients of the brains.

Figure 1: Transversal, sagittal and coronal slices through the x-ray CT scan of the physical phantom.

The ICP algorithm matches two 3D point clouds, where the number of points in the data sets is different; there exists no fixed pair-wise reference between the points of both data sets. The two data sets are called the base set and the matching set. The base point set is generated by sampling the considered surface of the image volume.
The respective point sets for registration are acquired with the tracking system. The tip of the pointing device is moved along the physical surface and points are recorded. The points are not in the tracker's absolute coordinate system, but measured relative to a marker mounted on the object (patient). The recorded point sets are registered using the modified ICP algorithm.

3. METHODS

For surface based registration rigid body transform is sufficient, since there are no systematic distortions, both in CT-image data and position data, provided by the tracking system. Rigid body motion is characterized by six degrees of freedom, both three for translation $\boldsymbol{t}=(t_x,t_y,t_z)^T$ into all directions, and rotation R. In this case we refer to the Euler angles in *(z,y',z'')* convention. The transform is described by the homogeneous 4 by 4 matrix (Goldstein 2006)

$$T = \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix}, \tag{1}$$

and

$$R = R_z R_{y'} R_{z''} \ , \tag{2}$$

built by the rotation matrices around the axes, fixed to the object

$$R_z = \begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ -\sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

$$R_{y'} = \begin{pmatrix} \cos\beta & 0 & -\sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}, \tag{3}$$

$$R_{z''} = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

with the rotation angles γ around the *z*-axis, β around *y'* and α around the *z''*. This is a popular notation with computer graphics and object movement. The calculation of the rotation matrix R is part of the registration algorithm described below.

3.1. Adapted ICP Algorithm

The iterative closest points (ICP) algorithm developed by Besl and McKay (Besl and McKay, 1992), is a recursive registration procedure, based on the idea of Procrustes analysis. Whereas Procrustes analysis strictly necessitates a rigid pairwise relationship of points in both datasets, which is a strong limitation, the ICP does not.

The ICP acts on a subset of the matching data set; the matching data is containing more data samples. From this set those points are selected, which are nearest neighbors to points of the base set. Each nearest neighbor pair builds a fixed assignment, valid during the current iteration step. Point data are centralized and normalized, i.e. the centroid of the point set is subtracted from the position values and the samples are normalized to standard deviation *1*. These procedures yield surfaces of the same size and basic overlay. But the surfaces are still not congruent, since rotation is not considered.

The rotation matrix is calculated by singular value decomposition (SVD) of the correlation matrix from above transformed data sets

$$C = X_B \cdot X_M^T \ . \tag{4}$$

The coordinate matrix X_B, consists of the base points (each column is a point). It is multiplied with the transpose of the matching point's matrix X_M. The correlation matrix C is decomposed into a diagonal matrix D of singular values and two orthonormal matrices U and V representing the base vectors of respective domains

$$C = UDV^T \ . \tag{5}$$

The rotation matrix R is the product of the vector bases U and V^T.

$$R = UV^T \tag{6}$$

The transformation, assessed in the current iteration, is applied to all points of the matching set and the algorithm is repeated by choosing a new set of nearest neighbors.

Registration is achieved when a stopping criterion is satisfied, e.g. minimum in distances of base to matching points.

3.1.1. Initialization

The ICP algorithm in general is rather robust with respect to the displacement of both initial datasets. But in the case of acquired images in the CT reference system and the position measures form the tracking system, the differences are too big. A direct application of the ICP algorithm would not yield substantial convergence, thus an initial overlay is necessary. For an initial rough guess of the orientation of both data sets, principal components analysis is performed with each particular coordinate set. The principal axes and the centroid are the parameters of the surrounding ellipsoid of each data set, giving an estimate of the position and orientation of both data clouds against each other. This allows a first initial registration prior to the ICP algorithm.

4. IMPLEMENTATION

This registration procedure is implemented in a rapid prototyping environment for surgical planning and navigation, based on Matlab®. The central module of this development environment is a seamless interface to tracking tools and other surgical instruments. The implementation is based on the Java library support of Matlab®, enabling a stable and real-time integration of all surgical navigation devices.

4.1. Architecture

The developed registration procedure is implemented upon a three layer architecture. It comprises

- application layer
  It is the top-most layer providing support for user-interaction, display and manipulation of medical image data in 3D. This is the general interface to human interaction.
- hardware abstraction layer
  This layer allows transparent access to the tracking and acquisition hardware. It encapsulates the vendor specific protocols, providing a unified scripting language for control of hardware devices interfacing the application layer. The hardware abstraction layer allows the connection of the application layer via the internet, enabling remote control of the tracking environment. This is of special interest if complex technical equipment is not suitable for a sterile surgical environment. It also enables the concurrent use of the same tracking hardware, maybe for development purposes or teaching.
- hardware layer
  In this layer the connection to one or more tracking and/or sensing devices is realized and proprietary communication is accomplished.

The principal part of the rapid prototyping environment is the hardware abstraction layer (HAL) (Zwettler and Backfrieder 2013), it allows seamless communication with all types of navigation hardware. In the center of the HAL is the DeviceServer (Zwettler and Backfrieder 2013b), it defines a communication standard enabling the integration of different hardware, like tracking environments, force sensors, haptic interaction devices or 3D surface scanners. These devices are directly attached to one or several host computers running the DeviceServer application. Thereby, communication between the attached devices and the DeviceServer is based on vendor-specific communication protocols and API's. When integrating a hardware device into the DeviceServer, abstraction from the complex API's, different messaging formats and transmission protocols is achieved. A compact set of harmonized scripting commands is defined for each device, utilizing extended Backus-Naur-Form (EBNF) grammar format for control command definition (ISO/IEC14977 1996).
Clients just communicate with the DeviceServer application over standard network protocols, thus achieving general connectivity and platform independence for all higher level applications demanding input and feedback from devices. The small set of HW-specific commands defined with the EBNF grammar is implemented with available vendor-specific API functionality. Commands can be transmitted to the DeviceServer via a console client, the application client port, a RAW network communication port and the telnet communication port, see Fig.2. The DeviceServer can handle an unrestricted number of clients concurrently. The EBNF command definition allows for wrapper generation in arbitrary programming languages. The command transfer is accomplished via network proxies to achieve programming language and platform independence. Currently C++ and Java wrapper generation is supported.

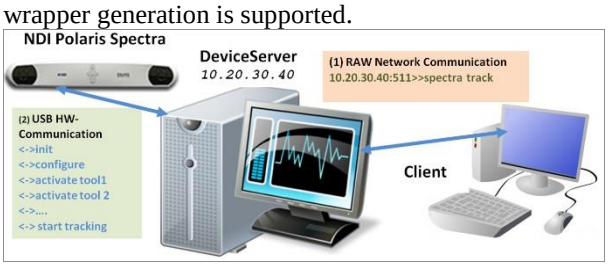

Figure 2: Sketch of a basic surgical navigation configuration. The devices are attached to the host computer running the DeviceServer as a central service. A client application communicates via network with the tools.

5. RESULTS

The surface based registration achieves proper results for registration. Results show a certain potential to substitute the newly developed ICP based method in place of the widely used point-to-point registration.

Figure 3: Phantom with attached position tool, surgical pointer and tracking unit (a), and segmented image space (b).

For testing the accuracy and usefulness of the novel registration procedure the position of five fiducial control markers (plastic spheres, 5mm diameter), mounted on an anthropomorphic head phantom, are measured with the registered tracking tools and assessed from image data. The displacement of position data is systematically calculated. Figure 3 shows a picture of the head phantom with attached fiducial markers and reference sensor and the pointing tool (a). A visualization of the segmented image volume is shown in Fig. 3.b. In this rendering the skull cap is displayed fully opaque. During the planning step the markers are segmented and the center of mass of each marker is calculated; this is taken as the markers image reference position. During the control step, the tip of the pointing-tool is moved to each marker, recording the position in the registered coordinate system. Figure 4 shows the recorded point cloud pattern relative to a 3D rendering of segmented objects. The upper row, cf. Fig. 4a and 4b, shows the unregistered points, the lower row, Fig. 4c and 4d, the registered sets. Both are rendered from a standard 3D view and a lateral camera position.

The upper skull is rendered slightly transparent with an opacity coefficient of 0.5. The images show sufficient congruence of the data sets.

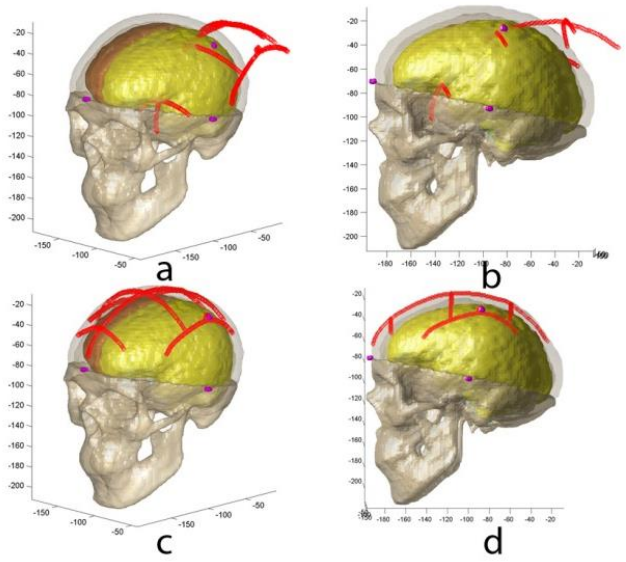

Figure 4: 3D Visualization of the head phantom as ttransparent rendering of the segmented objects in a standard 3D view (a) and from a lateral view (b). The measured and unregistered position data by sampling the upper skull with the tracking tool are displayed as red dots. Figures (c) and (d) show the dot cloud after ICP registration.

Table 1 summarizes the reference values R[1-5], the measured values M[1-5], and the resulting deviations. The mean difference is 2.93+/-0.92mm, indicating good registration. With a radius of the marker spheres of 2.5mm, the efficient accuracy is in the range of the tracker tolerance of 0.5mm.

Table 1: marker references

Name	x	y	z	Δr
R1	181.43	104.56	98.15	
M1	182,31	105,4	96,96	1,70
R2	179.63	59.58	56.47	
M2	177,92	61,32	58,05	2,91
R3	118.01	192.97	71.74	
M3	116,21	194,29	69,37	3,26
R4	56.49	84.93	28.53	
M4	57,31	85,33	26,12	2,58
R5	45.74	97.31	95.62	
M5	43,19	100,19	97,35	4,22
			ΣΔ	2.93+/-0.92

A rendering of the segmented objets, the fiducial markers, and the measured position of control points is shown in Fig. 5. From the numerical results and the renderings the evidence of sufficient overlap of both data sets is given. The methods is potentially useful for integration in an easy the use and robust registration tool.

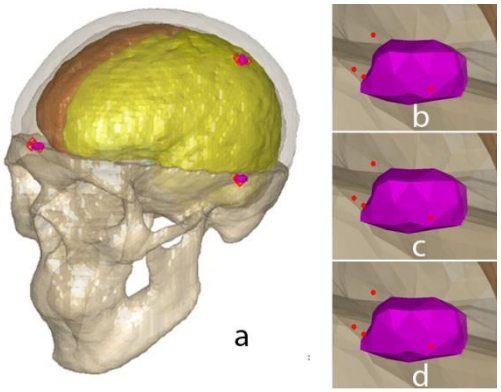

Figure 5: Visualization of the test procedure, rendering of the head phantom with segmented markers (turquoise spheres) with an overlay of measured reference positions as red dots (a), zoomed rendering of the three visible markers and respective control measures (b-d).

6. DISCUSSION

The development of surface based registration for registration of tracking coordinates and the patient domain proved to be reasonable. As shown by accurate registration results with the physical phantom random sampling of points by irregular movement of the pointing-device on the upper skull is easy and reliable; the curvature of the bone is distinct to provide good and unique matching of the contours, thus minimizing positioning errors during further navigation operations.
The full development of the registration algorithm in the Matlab® scripting language profits from small implementation cost and benefiting from the huge support with integrated mathematical instructions and graphical rendering options.
The Matlab® based system, comprising a hardware abstraction layer, not limited to devices from specific vendors, is an open alternative for easy development of new concepts and methods for image guided surgery. On top is the scripting language Matlab®, with its enormous functionality, enabling rapid development of even complex extensions to an existing navigation environment. Access to hardware tools is performed in real-time, display of complex sceneries may slightly lag behind. This can be solved by implementing critical code-pieces in Matlab-Mex, the native C interface.
The proposed registration method may not be applicable with soft tissue surfaces, since the great deformations of the surface during surgery by turgor will cause inconsistent registration. But for spine surgery, when bone screws need exact targeting into the vertebral body, not penetrating the vertebral channel, this method has high potential for surgical application.

REFERENCES

An, Y., Wang, M., Song, Z., 2015. A novel registration method for image-guided neurosurgery system based on stereo vision. Suppl. Bio-Med. Mat. & Eng. 26: S967-S973.

Aldana, P.R., MacGregor, T.L., James, H.E., Marcus, R.B. Jr, Indelicato, D.J., 2010. Titanium screws as fiducial markers for image-guided stereotactic proton irradiation in pediatric central nervous system tumors: a technical report. Pediatr Neurosurg. 2010;46(3):227-31.

Backfrieder, W., Zwettler, G., 2014. Robust surface based registration in an open framework for image guided surgery. Proceedings of the 3rd International Workshop on Innovative Simulation for Healthcare IWISH 2014, Bordeaux, Frankreich, 2014, pp. 36-41.

Benincasa, A., Clements, L., Herrell, D., Galloway, R., 2008. Feasibility study for image-guided kidney surgery: Assessment of required intraoperative surface for accurate physical to image space registrations. Medical Physics 35(9):4251-61.

Besl, P.J., McKay, N.D., 1992. A Method for registration of 3-D shapes. IEEE Trans. Pattern Analysis and Machine Inteligence, 14(2):239-56.

Bettschart, C., Kruse, A., Matthews, F., Zemann, W., Obwegeser, J.A., Grätz, K.W., Lübbers, H.T., 2014. Point-to-point registration with mandibulo-maxillary splint in open and closed jaw position. Evaluation of registration accuracy for computer-aided surgery of the mandible. J Craniomaxillofac Surg. 2012 Oct;40(7):592-8.

Blakeney, W.G., Khan, R.J., Wall, S.J., 2011. Computer-assisted techniques versus conventional guides for component alignment in total knee arthroplasty: a randomized controlled trial. J Bone Joint Surg Am 93:1377–1384.

Enchev,Y., 2009. Neuronavigation: geneology, reality, and prospects. Neurosurg Focus, 27(3): E11.

Evans, W.A., 1994. Approaches to intelligent information retrieval. *Information Processing and Management*, 7 (2):147–168.

Goldstein H., 2006. Klassische Mechanik, WILEY-VCH-Verlag, Weinheim 2006, S. 652.

Habor, D., Neuhaus. S., Vollborn, T., Wolfart, S., Radermacher, K., Heger, S., 2013. Model based assessment of vestibular jawbone thickness using high frequency 3D ultrasound micro-scanning. Proceedings of SPIE Medical Imaging, pp. 8675-83.

Hatiboglu, M.A., Weinberg , J.S., Suki, D., Rao, G., Prabhu, S.S., Shah, K., Jackson, E., Sawaya, R., 2009. Impact of intraoperative high-field magnetic resonance imaging guidance on glioma surgery: a prospective volumetric analysis. *Neurosurg* 64(6):1073–1081.

ISO/IEC 14977: 1996(E). Information technology – syntactic metalanguage – extended BNF. available from: http://www.cl.cam.ac.uk/~mgk25/iso-14977.pdf [accessed July 15, 2015].

Liu, Y., Kot, A., Drakopoulos, F., Yao, C., Fedorov, A., Enquobahrie, A., Clatz, O., Chrisochoides, NP.,2014. An ITK implementation of a physics-based non-rigid registration method for brain deformation in image-guided neurosurgery. Front Neuroinform. 2014 Apr 7;8:33.

Kelley, T.C., Swank, M.L., 2009. Role of navigation in total hip arthroplasty. *J Bone Joint Surg Am* 91(Suppl 1):153–158.

Malarme, P., Wikler, D., Warze'e, N., 2008. Digital operating room., 3(1): 145-148.

Mason, J.B., Fehring, T.K., Estok, R., Banel, D., Fahrbach, K., 2007. Meta-analysis of alignment outcomes in computer-assisted total knee arthroplasty surgery. *J Arthroplasty* 8:1097–1106.

Morea, C., Hayek, J.E., Oleskovicz, C., Dominguez, G.C., Chilvarquer, I., 2011. Precise insertion of orthodontic miniscrews with a stereolithographic surgical guide based on cone beam computed tomography data: a pilot study. Int J Oral Maxillofac Implants. 2011 Jul-Aug;26(4):860-5.

Nimsky, C., Ganslandt, O., Hastreiter, P.,Wang, R., Benner, T., Sorensen, A.G., Fahlbusch, R., 2005. Preoperative and intraoperative diffusion tensor imaging-based fiber tracking in glioma surgery. *Neurosurg* 56(1):130–138.

Paleologos, TS., Wadley, JP., Kitchen, ND., Thomas, DG., 2000. Clinical utility and cost-effectiveness of interactive image-guided craniotomy: clinical comparison between conventional and imageguided meningioma surgery. *Neurosurg* 47(1): p 40–48.

Reinbacher, KE., Pau, M., Wallner, J., Zemann, W., Klein, A., Gstettner, C., Aigner, R.M., Feichtinger, M., 2014. Minimal invasive biopsy of intraconal expansion by PET/CT/MRI image-guided navigation: A new method. J Craniomaxillofac Surg. 2014 Mar 19.

Scheufler, K.M., Franke, J., Eckardt, A., Dohmen, H., 2011. Accuracy of image-guided pedicle screw placement using intraoperative computed tomography-based navigation with automated referencing, part I: cervicothoracic spine. *Neurosurg* 69(4):782–795.

Verdú-López, F., Vanaclocha-Vanaclocha, V., Gozalbes -Esterelles, L., Sánchez-Pardo, M., 2014. Minimally invasive spine surgery in spinal infections. J Neurosurg Sci. 2014 Jun;58(2):45-56.

Zwettler, G., Backfrieder, W., 2013. Architecture and Design of a Generic Device Server for Virtual Reality Hardware Integration in Surgical Navigation - Lecture Notes in Computer Science, Vol. 8112(1), 2013, pp. 166-173.

Zwettler, G., Backfrieder, W., 2013b. Generic Device Server Implementation for Virtual Reality Hardware Integration in Surgical Training - Computer Aided Systems Theory (Eurocast 2013), Las Palmas, Spain,2013, pp. 118-119.

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DETERMINISTIC RECORD LINKAGE OF HEALTH DATA AS PREPARATORY WORK IN MODELLING AND SIMULATION – USE CASE: HOSPITALIZATIONS IN AUSTRIA

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ABSTRACT
Modelling and simulation as decision support in the health care sector often requires real world data. Complex models covering a variety of different areas within one model, for example outpatient and inpatient sector together, if treatment paths are examined, utilize different data sources. If those data sources are not linked, only point images are possible or the modeller has to define assumptions covering the gap of unlinked data. Therefore, a good record linkage allows more precise and reliable models and as a consequence better decision support. Within this paper a deterministic record linkage of two different data sources of the inpatient sector is proposed and tested. The results show a matching of 99.94% for initially 1.27 million data entries of one source. The linkage gives additional access to data from the outpatient sector. More information concerning a single patient is available, which can be utilized in different decision support models.

Keywords: record linkage, health data, modelling and simulation, decision support

1. INTRODUCTION

Models used for decision support in the health care sector are usually parameterized with real world data. Data sources range from aggregated data of publications, over raw data from studies to routinely collected data from insurance carriers, and others. This data usually is on patients and their specific problems within a specific context, for example a study on a specific disease, where information on prior diseases is not required. This is usually disease-centred. Models, especially within micro-based simulation methods as agent-based modelling, for example a model simulating general treatment chains of patients in the inpatient *and* outpatient sector researching the health care provision in specific regions, are, on the contrary, patient-centred according to the research question (Wurzer, Lorenz, Rößler, Hafner, Popper and Glock 2015). Here data on all of a patient's diseases is required. More information, longitudinal data like patient history or co-morbidities, concerning a patient's disease is needed. Data is needed in a individual-centred manner and not in a disease-centred manner; individuals are relevant. A linkage of different data sources opens up this necessary information. In (DuVall, Fraser, Rowe, Thomas and Mineau 2012) a case study, similar to the project presented within this paper, is described and they also argue for the necessity of a record linkage of different sources.

In this paper, routinely collected data from the inpatient sector, provided by the Main Association of Austrian Social Security Institutions and stored within the GapDRG database (see section 2 for details) is researched. Due to data privacy issues, routinely collected data of different sources is pseudonymized (e.g. MBDS minimum basic data set from the Federal Ministry of Health, lacking a personal identifier till the year 2015). This makes statistical analysis as well as modelling and simulation for decision support and health care planning very difficult. Data from insurance carriers (e.g. from the data source FoKo in Austria) is *event based*: whenever a hospital reports a new hospital admission or separation, a new data entry is generated, resulting in split *episodes*. To enable efficient, significant and quality assured data analysis (and further parameterization of models) for patient centred assertions, record linkage of these episodes is required.

A linkage for data of 2006 and 2007 hospital stays has already been implemented (Endel, Endel and Pfeffer 2012). New data for 2008 to 2011 is available from the insurance carrier of Lower Austria and the aim is to find a personal identifier for episodes provided by the Federal Ministry of Health (MBDS) based on linked episode-based events from insurance carriers (FoKo). The previously developed linkage routines cannot be applied to the new data any more (at least not a 100%), due to novel challenges that come with the new data and altered circumstances. But the basic algorithm of the previous linkage will be further developed, since it has been very successful in the past.

With this new linkage it is possible to access data for patients in the inpatient *and* outpatient sector together, so that information is available in a patient centred manner that makes models for decision support more reliable.

The paper is structured as following: section 2 gives an overview of the used data bases and the challenges that come with linking the data. Section 3 gives some information on the state of the art and describes the record linkage method. Section 4 presents the results and in section 5 conclusions are drawn.

2. DATA SOURCES TO BE LINKED

The GapDRG database - *General Approach for Patient-oriented Ambulant DRGs* - of the Main Association of Austrian Social Security Institutions (HVB) stores routinely collected data from different sources. Available data in general are as following:

- prescriptions,
- inpatient sector including diagnoses, treatments, duration of hospitalization, etc.,
- outpatient sector, including diagnoses, treatments, etc.,
- sick leaves including duration of sick leaves,
- data on medications,
- and others.

In GapDRG1 data is available for 2006 and 2007 for Austria. Here a linkage already has been conducted. In GapDRG2 data from 2008 to 2011 is available from the insurance carrier of Lower Austria.
The following two databases, both stored within GapDRG2, covering the inpatient sector from 2008 to 2011 for Lower Austria are being linked:

- FoKo (FOlgeKosten): data from insurance carriers
- MBDS (Minimum Basic Data Set): data from the Federal Minsitry of Health

A hospital reports admissions and discharges separately to those institutions, as presented in figure 1.

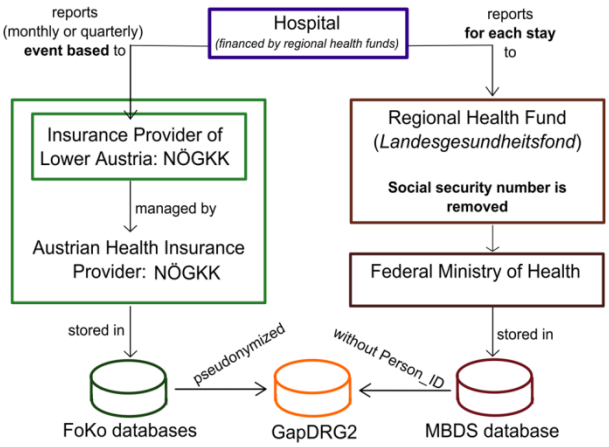

Figure 1: Databases to be Linked are FoKo (insurance carrier) and MBDS (Federal Ministry of Health).

Reports to the insurance carrier of Lower Austria are on a monthly or quarterly basis. This means that hospital stays may be split into so called *episodes*. On the other side, the hospital also reports every inpatient episode to the Regional Health Fund where the social security number is totally removed due to data privacy issues. Those data entries (for each stay) are then transferred to the Federal Ministry of Health. Here it has to be kept in mind, that it is not possible any more to determine if two hospital stays belong to one patient or not. Data from the insurance carrier of Lower Austria are then stored into the FoKo data bases. Here due to data privacy issues the data entries are pseudonymised, but it is still possible to determine if two hospital stays belong to the same patient or not.
FoKo and MBDS basically contain information on identical hospital stays with slightly different additional information. In MBDS further, more detailed information on the hospital episodes is available, like duration of the stay and additional to the main diagnoses up to four additional diagnoses, but also information on what procedures have been performed. But in MBDS there is no personal identifier. In FoKo on the other hand, there is a personal identifier, which enables further joining of the data to other data bases where the same identifier is used (sick leaves, medication, outpatient sector, etc).
Aim of this linkage is now to *find a unique person identifier for each episode in MBDS based on the information in FoKo.*

2.1. Challenges

The data linkage of course comes with some old and new challenges (Breitenecker, Urach, Miksch, Popper and Weisser 2011), that will be met within the proposed linkage:

1. **Reporting**: As mentioned before the hospital reports not only at the end of a hospital stay to the insurance carrier, but also during a stay. So in FoKo every time a new data entry is generated, as can be seen in figure 2 (green barrens).

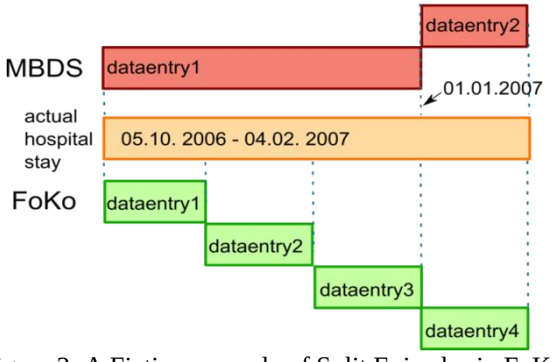

Figure 2: A Fictive example of Split Episodes in FoKo and in MBDS of One Hospital Stay.

A hospital stay, lasting over the boarder of a quarter/month of the year may be split into single episodes. In this case it is possible that, on the one hand, due to errors when entering

the data those entries don't point to the same hospital stay anymore and, on the other hand, that there are much more data entries (split episodes) to be matched to one data entry in MBDS. In MBDS hospital stays may also be split if the stay lasts over the boarder of the year or due to transfers.

2. **Amount of data**: In FoKo only data from the insurance carrier of Lower Austria is available and in MBDS data from other insurance carriers are included.
3. **Diagnoses**: Due to the fact that hospital stays may be split within FoKo (resp. MBDS), the recorded diagnoses also may differ for the split episodes (pointing at the same hospital stay). Furthermore, the recorded and reported diagnoses may also differ from FoKo to MBDS. Finally, the coding method itself for diagnoses in FoKo is slightly different to that in MBDS. For example the format of the ICD10 diagnoses: S82.1 versus S821.
4. **District**: A person may have one or more districts at a specific time. In FoKo the district recorded by the insurance carrier is used and in MBDS the district reported by the patient directly within the hospital stay is used. Later on the variable district, as it turns out, is also the most unreliable one.

3. RECORD LINKAGE

3.1. State of the Art

In the health care sector various record linkage methods exist and most of them are developed based on the existing data and their structure, as it is done with the linkage method in this paper. In (Silveira and Artmann 2009) a systematic review on the quality of probabilistic record linkage projects and methods is done and the paper shows that methods especially developed for existing data provide very good results.
In the very recent report by (Samhar 2017) challenges faced with semantic and syntactic interoperability of linking *event based data* as it is also done within this paper, are described. This shows once more that actual work and new methods are being developed and needed right now.

3.2. Linking Method

In GapDRG1 a record linkage has been developed for data from 2006 and 2007. The previous method will be slightly adapted and the new challenges, described in section 2.1 will be met and resolved. The record linkage basically consists of the following steps:

1. **Restrict both data bases to data of insurance carrier of Lower Austria:** In MBDS there is one variable *herkunft* that represents insurance carrier Lower Austria and in FoKo this variable is *leivtr*. Both will be restricted.
2. **Cleaning of data in FoKo:** a check is applied if data entries exist that are exactly the same, except for the artificial unique identifier. Those duplicates are eliminated.
3. **Define Matching Variables (MVs)**: After an analysis of the variables in FoKo and MBDS, some can be selected as so called matching variables (variables that represent the same information in both data bases). Those variables then have to be cleaned (also see section 2.1) for structural differences (Breitenecker, Urach, Miksch, Popper and Weisser 2011). See section 3.1. for details.
4. **Base Match**: Data entries in MBDS are unique due to the variable triple *hospital*, *year of stay* and *episode number* that are also matching variables. A base match, checking if a unique patient ID from FoKo exists for such a triple, is applied and assigns this patient ID to each unique episode in MBDS. See section 3.2. for details.
5. **Tests and Quality Checks**: After the Base Match some tests are applied and the remaining MVs are checked if they match as well. Based on those tests the iterative process starts where matching variables are varied. The order of these variations is derived from the tests here. For details see section 3.4.
6. **Iterative Matching Process with MVs**: the iterative process using all MVs with different matching conditions is applied. See section 3.4 for more details.

After steps 1 and 2 the remaining entries to be matched are as following:

- FoKo: 1,410,165 data entries (episodes)
- MBDS: 1,272,813 data entries (episodes)

All tests and matches are done with SQL. For the iterative matching process a lot of SQL queries are needed, especially for the combinations within the level matches. For this circumstance a automatically SQL script is generated with MATLAB by using string manipulation.

3.3. Matching Variables

In table 1 the ten identified MVs are described.

3.4. Base Match

The base match is very simple approach: if a unique patient ID in FoKo exists for the triple *hospital*, *episode number* and *year of stay*, this patient ID is assigned to the according (exact match of those three variables) episode in MBDS (here only one episode exists, since this triple is the primary key and identifies the data entry uniquely). A match in the other MVs is disregarded, since these three variables are the most trustworthy ones.

Table 1: The 10 Matching Variables identified in both data bases. Bold and underlined variables represent the unique identifier of MBDS data entries.

Variable	MBDS	FoKo
year of stay	is given	year of date-variable *end of stay*
begin of stay	is given	is given, but episode may be split
end of stay	is given	is given, but episode may be split
hospital	is given	is given, but 56,330 entries are missing
episode number	is given	is given, but 26,453 entries are missing
diagnosis	main and additional diagnoses are given, but only main diagnoses are used	is given, but 3 data entries are missing, others may differ from MBDS (see section 2.1, challenge 3)
age	age at discharge is given and may be inaccurate, therefore additional conditions of consistency +/- 1 year are allowed.	*person_id* is given and age can be retrieved from another data base by using this ID and variable on *birth year*. Calculation of *age* by using *birth year* and *year of hospital stay* is possible.
gender	gender is given, but may be inaccurate. "M" for male and "W" for female.	*person_id* is given and gender can be retrieved from another data base by using this ID and variable on *gender*
death	year of *end of stay* together with being 'S' for death is used.	year of death is given
district	is given	*person_id* is given and district can be retrieved from another data base by using this ID in accordance of insurance carrier and time of insurance.

In the base match 611.591 episodes in MBDS can be matched (48.05%).

3.5. Tests and Quality Checks of Base Match

Since in the base match the other matching variables have been disregarded it is of course interesting to know the degree of consistency anyway. Consistency checks are applied directly with SQL by checking if those data entries are equal (using "="). Results can be seen in table 2.

Table 2: Degree of Consistency in other MVs after the Base Match.

Matching Variables	Degree of Consistency	
	Total	In %
Begin of stay	611,489	99,98%
End of stay	611,075	99,92%
Diagnosis	579,180	94,70%
Age	315,758	51,63%
Age +/-1 OR exact match	611,124	99,92%
Gender	610,714	99,86%
District	5,657	0,92%
death	10,614	--

Consistency in *begin of stay* and *end of stay* (exact date) is very good, as well as *gender* and also *diagnoses*. The check of consistency for *age* (age at discharge in MBDS compared to calculated age in FoKo based on *end of stay* and *birth year*) is not so good. The check of consistency with +/- 1 year due to calculation inaccuracies on the other hand gives a very good degree of consistency.

In the iterative matching process (see section 3.4) matching variables are varied (all variables have to match except 1, 2, 3...) and the remaining variables are checked for consistency. This results in a huge amount of combinations of MVs that are left disregarded within the different levels. The order in which the MVs are varied within the matching process is retrieved from exactly these tests (reverse order of matching qualities), meaning that for *example begin of stay* is left disregarded in the variations at the end due to its good matching "qualities" in these tests.

3.6. Iterative Matching Process

After the base match the iterative record linkage starts with the remaining data entries in FoKo and MBDS. Here all matching variables are used together: First there are the so called *level matches* up to level 6, each of them consisting of two so called *steps*.

In each step/level whenever matches are found the next step/level is conducted with the remaining data entries of both data bases. The found matches are removed from the further matching process. When level 6 is completed, the process starts at level 1 again with the remaining data entries. This is called iteration. A schematic representation of the level matches and iterations can be seen in figure 3.

The red numbers show the time line of the linkage process starting with 1 at the base match (orange rectangle), 2 for storing the found matches of the base match and 3 transferring the remaining - still to be matched - data entries of FoKo and MBDS. Then the level matches start with level 0, meaning consistency – being equal - in all MVs. Here again the match is

conducted (red 4), found matches – if person identifier is unique – stored into "Matches" (red 5) and remaining data entries used for Level 1 (red 6).

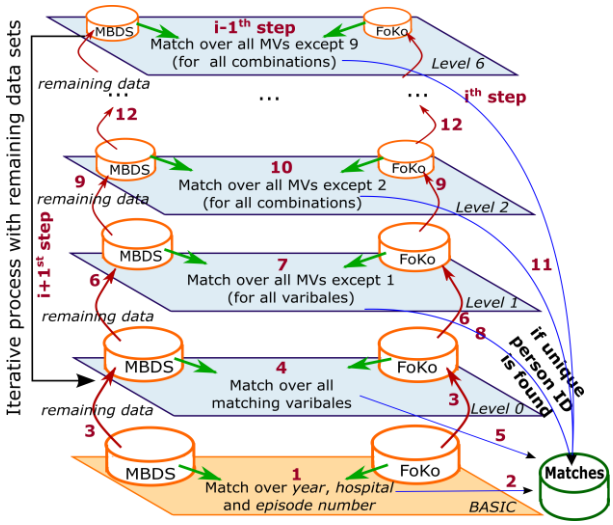

Figure 3: Schematic Representation of the Record Linkage with its Level Matches and Iterations after the Base Match.

Level 1 means consistency in all MVs except 1. Here "except 1" means that the MV(s) are varied, so all of the MVs are disregarded once. The order, which variable is left outside is in reverse order as the degree of consistency after the base match (see table 2).
Level 2 means that all except 2 MVs have to match, and so on. There are 10 MVs and as a consequence the number of variations in level 1 is 10 (each of the MVs is left disregarded once). In level 2 at each step 2 MVs are left disregarded, resulting in 45 variations (combination of the 10 MVs). In level 3 there are 120 variations. As a result – programming those variations by hand would be very time intensive – the whole record linkage is semi-automatic (SQL Code that is partially constructed with MATLAB).
Furthermore, within the level matches there are two steps (not shown in figure 3) concerning the excluded MV(s) – of course these two steps are applied in levels 1 to 6 and not in level 0:

- Step 1: allows missing data, meaning that at least one (either in FoKo or in MBDS) MV within the MV(s) that are excluded is NULL (missing).
- Step 2: allows missing data OR inconsistency, meaning either one or both entries is NULL or contradicting (missing or contradicting).

Example: Level 1/Step 1: a match is included if gender in FoKo is "M", gender in MBDS is NULL and all other MVs are the same. Level 1/Step 2: a match is included if gender in FoKo is "M", gender in MBDS is "W" and all other MVs are the same.

Step 2 guarantees that errors in reporting as mentioned within the challenges in section 2.1 are eliminated. In the first step only checks with missing data are permitted, and only then in the second step contradicting values are permitted, because in step 1 no one knows if it would be a match if the entry is available and in step 2 it is for sure that it is contradicting (or an error in reporting). Here again the order of the single parts within the matching process is relevant to guarantee the best possible outcome of the matches.
This is done until level 6. Further levels, like level 7, would be very unreliable, meaning that it is a match except in 7 (out of 10) MVs. After level 6 the next iteration starts at level 1 again with the remaining data entries in FoKo and MBDS until no entries are left or until no matching entries can be found any more. This procedure guarantees the best possible matches due to the chronology of the different matches.

4. RESULTS

The results of the record linkage can be seen in table 3. Most matches (after the base match) have been found whenever the *episode number* was excluded. This is a rather long number where errors may be more likely.

Table 3: Results of the Record Linkage Together with Information in which Level and Iteration it was found.

Iteration / Level	In Foko remaining	In MBDS remaining	Match	Match total in %
Start	1,410,165	1,272,813	--	--
Base Match	794,294	661,222	611,591	48.05%
1 /1	794,256	661,184	38	48.05%
1 / 2	780,741	647,656	13,528	49.11%
1 / 3	232,976	99,767	547,889	92.16%
1 / 4	189,629	18,262	81,505	98.56%
1 / 5	198,599	18,235	27	98.56%
1 / 6	184,342	1,418	16,817	99.88%
2 / 3	184,310	1,384	34	99.89%
2 / 4	184,285	1,359	25	99.89%
2 / 5	183,764	830	529	99.93%
2 / 6	183,654	713	117	99.94%
3 / 4	183,653	712	1	99.94%
3 / 5	**183,650**	**709**	**3**	**99.94%**

After level 3 (3 MVs have been excluded) most of the remaining matches have been found (92.16%) and that is due to the fact that the previous mentioned triple of *hospital*, *episode number* and *year of stay* have been excluded (Step 1 or Step2, NULL or contradicting). After 3 *iterations* no significant number of matches can be found (in iteration 3 only 4 additional matches occur)

and the record linkage stopped with a total of 99.94% assigned patients to hospital episodes in MBDS, leaving 709 data entries in MBDS without personal identifier. This *deterministic* record linkage, if being applied to the same data again, produces the same results as shown in table 3. Within the proposed record linkage method the sequence of the single steps of the matching is important, because it guarantees that in each step the best possible outcome is produced.

A huge benefit and further development of this new linkage process, compared to the linkage in GapDRG1, is the fact that more information concerning the level and iteration of the found match is available: an additional data entry to each match provided as a string shows the number of iteration and number of level it was found in. This means that the modeller or data analyst can decide (on its own or based on the research question) which match will be accepted in further analysis or for parameterization of simulation models. More information on which specific matching variable was excluded in the level/iteration while the match was found can – hypothetically – be obtained as well, if necessary.

Another result of this linkage is the fact, that, if more data of the same structure, for example for the whole of Austria is provided, the linkage method can be applied quickly. Finally, with this matching where for (nearly) each episode in the inpatient sector a personal identifier was found, other information for this person is available, like prescription data, sick leaves, services in the outpatient sector, etc (see section 2 on data in the GapDRG database). Now, for example, the prevalence of various diseases can be calculated by using inpatient and outpatient data together reducing uncertainties by using only one data source. This is important in modelling and simulation, because less assumptions have to be made.

5. CONCLUSION

Using good data for parameterization in modelling and simulation is essential to designing a model, especially when it is used in such a sensitive area as decision support in the health care sector. Different data sources give different point images of the current or past situation and therefore gaining more information (linked information) is nearly impossible. Usually a lot of assumptions are made, which makes the model unreliable. In this paper, a deterministic record linkage of two different data sources concerning hospitalizations is further developed and tested. With these linked data sources it is now possible to retrieve much more information than just on hospitalizations, as it is now possible to add information from outpatient care, sick leaves or prescriptions. As a result, for example, modelling of whole treatment chains is possible or modelling the health care provision in different regions of Austria.

A record linkage of historic data within the database GapDRG from the Main Association of Social Security Institutions has been performed before. The proposed improved procedure met new challenges like different sizes of data sources (Lower Austria vs. Austria) or record errors due to split episodes or simple syntactic errors (diagnoses) which have been addressed. The main innovations of this procedure include a significant improvement of previously developed methods, mainly concerning reproducibility, stability and adaptability to new data and a documentation on every single step of the linkage procedure, allowing researchers to comprehend the origin of a link and adapt their data analysis strategies.

The procedure achieves the best possible outcome for the new data sets and is highly suitable to be used within new data in a semi-automatic way, which also enables new simulations faster. In (Bohensky 2010) a systematic review is done and they conclude that an incomplete record linkage is very problematic for further analysis. The record linkage proposed within this paper is nearly complete and therefore suitable for further use for parameterization of simulation models.

ACKNOWLEDGMENTS

The K-Project Dexhelpp as part of COMET – Competence Centres for Excellent Technologies - is sponsored by BMVIT, BMFW and the city of Vienna. The COMET project is organized by FFG.

REFERENCES

Bohensky M. A., 2010. Data linkage: a powerful research tool with potential problems. BMC Health Serv Res 10, 346.

Breitenecker F., Miksch F., Popper N., Urach C., Weisser A., 2011. Dealing with Health Care Data of the Austrian Social Security System. Medical Decision Making, 31 (1), E51.

DuVall S. L., Fraser A. M., Rowe K., Thomas A., Mineau G. P., 2012. Evaluation of record linkage between a large healthcare provider and the Utah Population Database. J Am Med Inform Assoc 19, e54-59.

Endel F., Endel G., Pfeffer N., 2012. Routine Data in HTA: Record Linkage in Austria's GAP-DRG Database. Poster at ISPOR 15th Annual European Congress. November 3-7. Berlin, Germany.

Samhar M., 2017. The 'PEARL' Data Warehouse: Initial Challenges Faced with Semantic and Syntactic Interoperability. Studies in Health Technology and Informatics pp. 156–160. doi:10.3233/978-1-61499-753-5-156

Silveira D. P., Artmann E., 2009. Accuracy of probabilistic record linkage applied to health databases: systematic review. Rev Saude Publica 43, pp. 875–882.

Wurzer G., Lorenz W., Rössler M., Hafner I., Popper N., Glock B., 2015. ((MODYPLAN)) – Early-Stage Hospital Simulation with Emphasis on Cross-Clinical Treatment Chains. Proceedings of the Symposium on Simulation for Architecture and Urban Design, pp. 97-100. April 12 – 15, Washington D.C. (USA).

SPATIAL PSYCHIATRIC HOSPITALIZATION MODELLING IN AN INTERNATIONAL SETTING – AN AGENT BASED APPROACH

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ABSTRACT
Modeling and simulation in international health care resource planning and future strategy testing has growing impact and importance. Within the CEPHOS-Link FP7 project a dynamic agent-based model is integrated for Austria, Slovenia and the Veneto region of Italy for answering questions defined in PICO structure for psychiatric disease hospitalization and re-hospitalization under special constraints using big national claims databases combined by using a well-defined data pooling process. The basis for the dynamic simulation process is a generic population concept (GEPOC) developed within the DEXHELPP consortia project in Austria and parameterized and calibrated using EUROSTAT and national statistics databases. Regional concepts are simulated based on NUTS-3 distance of service information integrated by driving time calculations. All results are gathered on a personal level and depicted and described on age gender groups added by cost-information.

Keywords: health care simulation, agent-based model, spatial dynamics, international claims data

1. INTRODUCTION

High re-hospitalization rates are often regarded as an indicator of malfunctioning of hospitals and health care systems. This applies especially to mental health care where the term “revolving door psychiatry” has been coined for this situation. However, when evaluating mental health care systems, international comparisons of psychiatric re-hospitalization rates derived from routinely collected health care data are hampered by different ways of establishing them in different countries with different health care systems and different data collection routines, and cannot be used at face value.

1.1. General objective

The overall objective of the CEPHOS-LINK project was to compare with a common study protocol psychiatric re-hospitalization rates in six European countries (Austria, Finland, Italy/Veneto, Norway, Romania, and Slovenia) for adult patients, and to identify predictors be regression analyses in a retrospective cohort study design, first locally for each country dataset and then centrally with a pooled dataset. A crucial innovative aspect and challenge of this project was that observational data from large national electronic health care registries in six different countries with different care systems and different data collection routines were used. The major advantage of this approach is that very large unselected patient populations can be applied to all countries thereby reducing the “methodological noise” inherent in systematic reviews of separate studies.

The CEPHOS –LINK patient dataset for the pooled analysis consists of finally 225.600 patients fulfilling the inclusion criteria. Besides the development of a data pooling protocol.

1.2. The modelling objective

Besides classical statistical analysis (logistic regression and Cox- regression models) questions regarding long time behavior and planning of resources arise. As identified by systematic literature research dynamic modelling methods are up to now underrepresented in the solution of re-hospitalization research (Urach, Zauner, Wahlbeck, Haaramo and Popper 2016) These demand is iteratively formulated within three research questions defined based on concepts used in health technology assessment (HTA) and evidence based medicine (EBM) called PICO, especially influenced by Aslam and Emmanuel (Aslam, Emmanuel 2010). Within this concept the **p**opulation, **i**nnovation **c**omparator and **o**utcomes are defined. In short these are:

- Task A: How will first hospitalizations and re-hospitalizations change in the future due to demographic change?

- Task B: How does theoretical improvement of the care structure in certain NUTS-3 regions impact re-hospitalization rates?
- Task C: What is the possible impact of rising diabetes prevalence on psychiatric re-hospitalizations?

Task B is based on findings of the Italian research partner within CEPHOS-Link (Donisi, Tadeschi, Wahlbeck, Haaramo and Amaddeo 2016). Task C is based on results from descriptive claims data analysis and literature research (Sprah, Dernovsek, Wahlbeck and Haaramo, 2017). In all tasks the entire populations are adult patients (+18 years old), tasks A-C describe the innovation. The comparator is the actual situation out of the claims data (Breitenecker et al. 2011) and the outcomes of interest are the number of hospitalizations/re-hospitalizations per year, gender, diagnosis group and age group. As well as the total costs – to get comparable results the purchasing power parity (ppp) cost data sets are implemented.

1.3. Statistical analyses

Each country identified adult patients (18+ years old), discharged for the first time over a period of 12 months from a psychiatric inpatient bed with a primary functional psychiatric diagnosis (ICD-10 F2-F6). These patients were then followed up over one year. One major restriction was that there was no censoring for death during follow-up included in the analyses.

Local single level logistic and Cox regression were performed in order to identify predictors for psychiatric re-hospitalization, as well as for re-hospitalization to any hospital. To guarantee comparable results and techniques the patient cohort was defined iteratively with a stepwise quality assessment lead by IMEHPS Research.

The predictor variables used in the logistic regressions where the gender, the age of the patients as a dichotomous variable based on the age distribution in the six partner countries, the classification of the disease (F2 or F30 or F31 vs. the other F3 diagnoses up to F6) and the length of stay of the index hospitalization. In a further step physical comorbidities identified by the additional diagnoses at the index hospitalizations are taken into as additional predictor.

Multilevel logistic regression analyses were performed with additional contextual/geographical variables on the NUTS3 level of a patient's place of residence (degree of urbanity, Gross Domestic Product).

For countries having a broader data set on linked data on single person level also outpatient contacts of the patients after discharge – Austria, Slovenia and the Veneto region of Italy - from the index hospitalizations, analyses for the three potential extramural care events:

- Ambulatory care (a patient visits a psychiatric doctor/a psychiatric service and gets treatment/advice/ therapy for a short time period - usually less than one hour – and leaves again)
- Day care (patients visit a psychiatric day care unit for several hours and participate in a structured therapeutic program)
- Mobile service (a psychiatrist/psychiatric care team visits a patient at home/or similar environment)

are realized using the time line information of the extramural events and firstly analyzing for any event. In the last step the logistic regressions are split up for the three types of contacts and influence of outpatient contacts and re-hospitalization under the given predictive parameters has been discussed.

2. GENERAL POPULATION MODEL

As the patient always poses the center of interest, valid prognostic modelling for decision support in the health care system is only possible if the underlying population is predicted validly as well. Doubtlessly long-term epidemiological or health-technology-assessment models can never be valid if the underlying population growth or decay is not considered. This becomes clear thinking about an average chance of about one percent that an Austrian inhabitant leaves the country or dies during one year. Hence, on the average, every 100th person is "replaced" by an immigrant or newborn child every year leading to a highly fluctuating population.

Moreover a valid population model is not only a necessary part of any model in health-care science; it is also a reusable basis model for different applications.

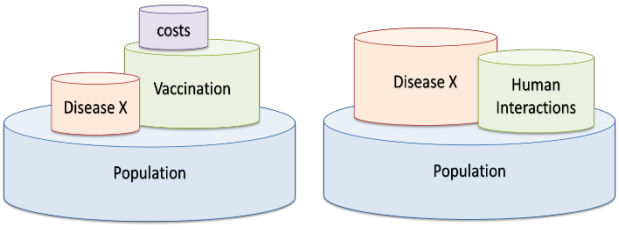

Figure 1: Left: Cost-Effectiveness model for disease X based on a population model. Right: Epidemics model for infectious disease X based on a population model.

2.1. GEPOC - Population Model

Although the Generic-Population-Concept (GEPOC) originally does not pose for a model, but for a generic modelling concept summarized in a broad handbook, the main result of the GEPOC project was achieved by a versatile agent-based model to simulate population of Austria until 2050 (starting in 2006). Hence we will moreover identify this model by the name of the project.

The agent-based modelling techniques is generally applicable for dynamic modelling and simulation of the underlying tasks A, B and C as the focus lies on populations with spatial constraints like restrictions regarding care and the social status, as well as heterogeneous patient characteristics. In the literature agent-based modelling in the hospital care setting is more often used for local in-house simulation especially in hospital wards (Taboada, Cabrera, Epelde, Iglesias, Luque 2013) but there are also new papers in the field of combined effects modelling (Silverman, Hanrahan, Bharathy, Gordon, Johnson, 2015; Kalton, Falconer, Docherty, Alevras, Brann, Johnson, 2016). Generelly often economic effects on heterogeneous patient care is under discussion. For such problems, agent-based techniques seems to be the method to choose.

As Austria's population consists of individuals, they are represented by agents (or individual-agents) in the model. As it might not be possible to simulate millions of agents at once, finally one model agent stands for a hole aggregate of people (e.g. 10 or 100 henceforth denoted as $\boldsymbol{K}$) which all behave alike.
As model borders do not take into account to simulate immigrants before they immigrated, a second type of agent needs to be introduced: the government-agent. This type of agent is responsible for the creation of newly immigrated individual-agents (Bicher et al. 2015, Bicher and Popper 2016).

2.2. Parameterization

While the available data is given on the aggregate level it is main task of the parameterization process to calculate parameter-values for the individual level – i.e. probabilities that hold for **one representative** person = agent for one model time-step.
While total numbers for a specific point in time (like total number of Austrian inhabitants at 2003.01.01) can be processed quite easily, classically by simple divisions – e.g.

$$P(\text{agent's sex} = \text{female}) = \frac{|\text{number of female persons in Austria}|}{|\text{number of total persons in Austria}|},$$

it is a little bit more difficult to process "differential-numbers", i.e. numbers that are valid for a specific time-span (like total number of immigrants, emigrants,… during a year), to probabilities that are valid for one specific time-step as the length of the time-step is arbitrary.

Representative for all other "differential" parameters we show the parameter calculation process on the example of the death-probability. Given the number

$$X := \text{“}\textit{average yearly deaths of 100000 Austrians during year}= y \textit{ for age=}a \textit{ and sex=}s\text{”}$$

The corresponding parameter value $Pd(t, \delta, a, s)$ (days as unit for δ) can be approximated by

$$Pd(t, \delta, a, s) = 1 - \left(1 - \frac{X}{10000}\right)^{\frac{\delta}{365}},$$

which is valid for all $t \in [y, y + 1)$. This formula can be attributed to the geometric distribution.

The model was implemented in Python 3 and (usually) executed with CPython 3.3. Attempts to execute the model with the faster Python like Pypy 3.3 unfortunately failed due to incompatibilities with the python numeric package NumPy.
The source-code is structured into four different classes: The simulation-class is responsible for the initialization and the dynamics of the model. It creates and addresses instances of the agent-class and additionally takes on the role of the government-agent. It furthermore creates and controls an instance of the protocol-class and the sampler-class. Each instance of the agent-class poses for one individual-agent and hence represents K persons in reality. The protocol-class is responsible to save all necessary data of the simulation run. The sampler-class is responsible for the parameterization of the data-driven background of the model. We do not want to go into detail about the specific classes.

2.3. Model Validation

Validation of a model denotes the process wherein the model respectively the model results are finally compared to reality. This is necessary in order to finally state the claim: The model is *valid* and can be used to predict reliable prognosis, or the model is *invalid* and needs to be re-conceptualized. In reality the result of this process is usually neither black or white, but much more a set of nuances on a grey-scale stating which parts of the model produce rather valid results and which parts need to be treated carefully as errors might be involved. It is a general fact that, as we cannot look into the future, no predictive model can be said to be perfectly valid.

As the data required to parameterize the model was also gained from Statistics Austria, this process directly compares the modelling method with the statistical regression-method. The connection of the claimed Statistics Austria data to both models is visualized in Figure 2.

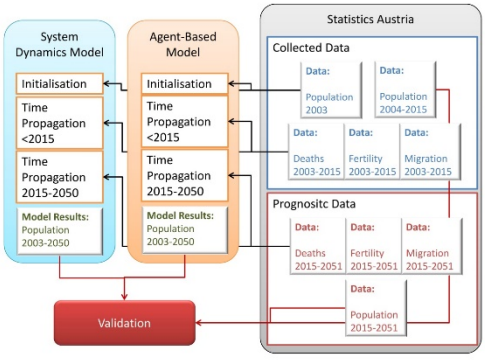

Figure 2: Summary of the connection between Statistics Austria and the two GEPOC models, the agent-based model and the system-dynamics model. Black arrows indicate the usage of data for parameterization. Red arrows indicate usage and comparison of data during the validation process.

The validation process was very successful. We compared the agent-based model (mainly) with $\delta = 365\ days$ and $\delta = 30\ days$ with data collected from Statistics Austria planning to show that the model delivers valid results for different step-sizes. Some chosen results of this process can be seen in Figures 3-4

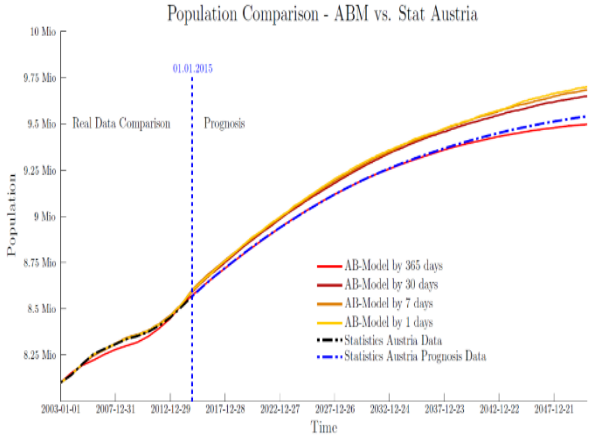

Figure 3: Temporal development of the total population. Results of simulation with different model time-steps compared with Statistics Austria data/prognosis.

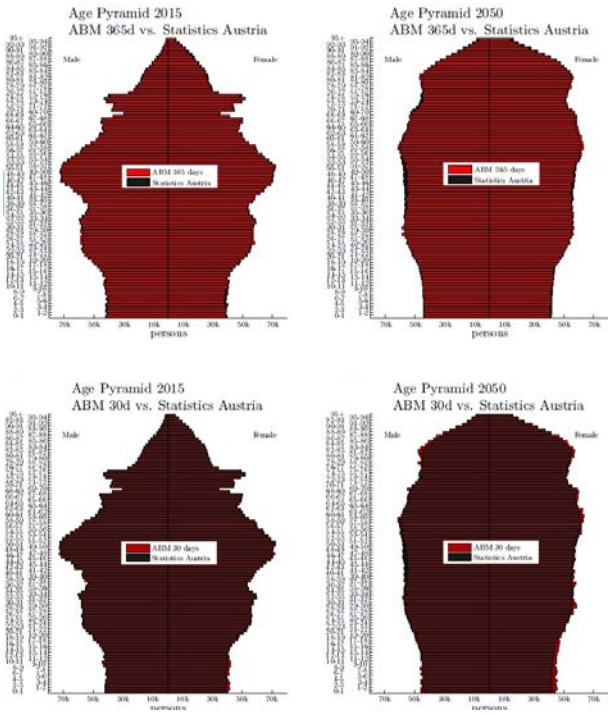

Figure 4: Age pyramid resulting from the model vs. age-pyramid resulting from Statistics Austria data/prognosis. Only for the 365 day execution slight differences can be seen for 0-5 year old women.

3. DETAILED MODEL DEFINITION

In order to fulfil the three tasks described in section 1.2 GEPOC has to be extended by a couple of new functionalities/modules:

- Each agent (statistical representative for a real person) has a possibility to have a hospital stay. Herein it receives a diagnosis which influences how long the patient stays in the hospital and whether the agent might return to a hospital after some time, i.e. has a readmission.
- Each NUTS3 region has a specific mean-driving time to a hospital which influences the re-hospitalization probability for all inhabitants.
- Each person may additionally suffer from Diabetes Mellitus which itself increases the readmission probability.

Moreover GEPOC used as a part of CEPHOS-Link is always executed with the total population of about 8 - 9Mio. Agents (i.e. $K = 1$) to avoid rounding errors and, more importantly, confusions which might lead to a lack of credibility. Moreover yearly steps are used as all input data is given at a yearly basis. Note that yearly steps does not imply that every step is 365 days long (leap-years).

3.1.1. Task A: Hospitalization and re-hospitalization

In addition to the defined agent behavior in the GEPOC section each agent (standing for one representative real person) has a probability to have a called index-stay during each time-step. By this term we refer to the first

hospital-stay of a person (agent) in a year which is not a readmission. I.e. any agent that did not already have a readmission in the observed year has a certain probability

$$Pi(a,s),$$

wherein a, s stand for age and sex of the agent, to visit a fictional hospital at some point during the observed year. Note that this probability, in the contrast to almost all standard GEPOC parameters, does not depend on time. In case the person is (randomly) selected to do so, first of all the agent receives one of two diagnosis: *psychotic* or *nonpsychotic*:

$$P(Diagnosis = psychotic) =: Pdp(a,s),$$
$$P(Diagnosis = nonpsychotic) =: Pdn(a,s),$$

We will refer to this diagnosis as d henceforth. Dependent on this diagnosis the length of the stay is sampled. This is either done using a gamma-variate random variable or sampling a number of days by a discrete distribution. In any case this duration must exceed one day (one night) by definition:

$$Length\ of\ stay(a,s,d) \sim \Gamma(\alpha,\beta)\ or\ discrete.$$

Moreover each agent might have a chance to be readmitted at a later point in time. Although this might basically sound acausal, the question whether or not an agent is readmitted is answered immediately at the point of the index stay due to data reasons. Therefore we have a probability

$$Pr(a,s,d)$$

deciding about if an agent is readmitted. In case an agent is chosen to do so two time-spans are sampled, once more either by gamma-variate random numbers or by discrete distributions:

$$Time\ until\ readmission(a,s,d) \sim \Gamma(\alpha,\beta)\ or\ discrete.$$
$$Length\ of\ readmission \sim \Gamma(\alpha,\beta)\ or\ discrete.$$

All of these time-spans must not be shorter than one day (night). The time until readmission must not exceed 365 days.

3.1.2. Task B: Mean Driving Time Influences Readmission Probability

In order to have the re-hospitalization probability depend on the mean driving time to a hospital in a specific NUTS3 region, the NUTS3 extended GEPOC version (described before) is used. Moreover let r define the region an agent inhabit and $F(r)$ a specific factor that indicates how much higher the probability for a readmission for a specific NUTS3 region r is. In most cases two NUTS3 regions were identified, that have a significantly higher readmission rate than the rest. Hence $F(r) > 1$ for two regions and 1 for all others. We receive:

$$Pr(a,s,d,r) = F(r) \cdot Pr(a,s,d) \cdot K,$$

for a constant compensation factor K (slightly smaller than 1) which had to be calibrated, so that the new simulation results do not differ from the old ones in total (total Austria).
All other parts of the model remained untouched.

3.1.3. Task C: Diabetes Mellitus

Given only the total prevalence of diabetes in Austria, Veneto and Slovenia the model, but not the incidence numbers the model had to be parameterized differently than the hospitalizations – it is not possible to correctly calculate a probability for a diabetes case by knowing only the absolute numbers per year. Therefore the Government Agent (described in the GEPOC Section) takes care about the number of diabetes diseases in the model. It observes the number of diabetes cases (per sex and age cohort) at the beginning of each time-step and randomly "distributes" new diabetes cases randomly among the population to fit the diabetes-prevalence numbers of the actual year. This yet very macabre way of modelling a disease is the only way to use prevalence data to directly parameterize disease models. Otherwise a very demanding calibration process had to be done.
Say an agent's diabetes status D is either $true$ or $false$ and $F_2(D)$ ($= 1$ for $false$, > 1 for $true$) denotes the influence of diabetes on being readmitted to a hospital the probability for a readmission is given by the following probability:

$$Pr(a,s,d,r,D) := F_2(D) \cdot Pr(a,s,d,r) \cdot K_2$$
$$= F_2(D) \cdot F(r) \cdot Pr(a,s,d) \cdot K \cdot K_2$$

Once again, a compensating factor $K_2 < 1$ had to be calibrated.

4. PARAMETRIZATION

4.1. Hospitalization Specific Parameters

Without going into detail about data acquisition at this specific stage (it is briefly explained in <somewhere else>) we will only explain which and how data was used to parameterize the model.
First of all probabilities

$$Pi(a,s), Pr(a,s)$$

could be determined using known methods (dividing number of known index-stays or readmissions by total population or total number of index-stays respectively). We chose numbers for 2006 (Austria) and 2013 (Slovenia, Veneto) as reference for these calculations. Age classes 65+ had to be dealt as a whole. This was a matter of the sample size as for certain age classes >65 not even one index-stay was recorded in 2006/2013 which would have perturbed the model parameterization by (definitely wrong) $Pi(a,s) = 0$.
In order to sample a length of a stay or the time between two hospital-stays was initially tried to be fitted by a gamma distribution dependent on age and sex (and diagnosis). Hence two age, sex (and diagnosis) parameters α and β were determined using a standard maximum-likelihood method. In case the gamma-distribution turned out to be a bad match for the given data, a discrete distribution was fitted – i.e. the numbers

$$P(time\ interval = x\ days\ |s,a,(d)), x \in \{1,\dots,365\}$$

were determined by a histogram. Which method was used for which parameter can be seen in Table 1.

Table 1: Which distribution was used to sample which time-span for all three considered regions

	Austria	**Slovenia**	**Veneto**
Length of index-stay	gamma-distribution	gamma-distribution	gamma-distribution
Time until readmission	discrete	discrete	discrete
Length or readmission -stay	gamma-distribution	discrete	discrete

In the following Figures 5 and 6 exemplarily show the results of the gamma distribution fit, estimated with a Maximum Likelihood estimator.

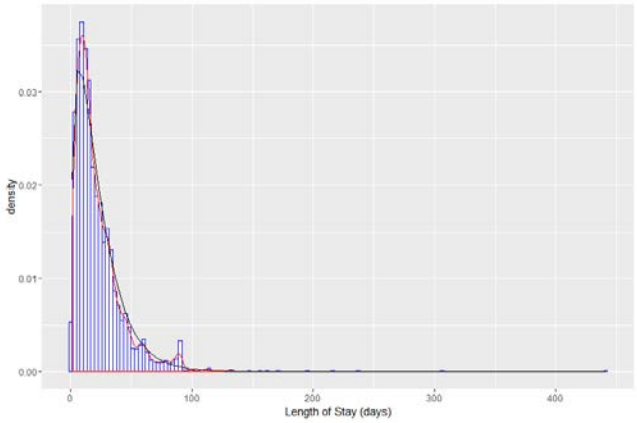

Figure 4: Length of stays according density function (red) overlayed with a gamma density function (black) of the Veneto region patients

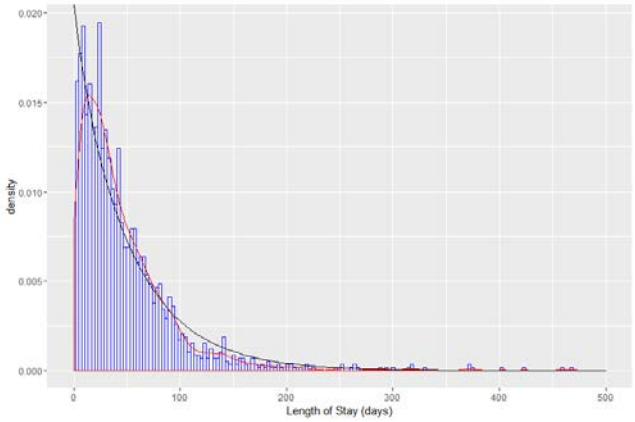

Figure 6: Length of stays according density function (red) overlayed with a gamma density function (black) of the Slovenian patients

4.2. Diabetes Specific Parameters

Diabetes Mellitus (DM) prevalence data was available for two specific points in time:

- Total number of DM cases for 2010 and Austria, Slovenia and Italy/Veneto with following subcategories: No. of Female Cases, No. of Male Cases, No. of cases [20-39], No. of cases [40-59], No. of cases [60,79]
- Total number of DM cases (estimation) for 2030 and Austria, Slovenia and Italy with following subcategories: No. of Female Cases, No. of Male Cases, No. of cases [20-39], No. of cases [40-59], No. of cases [60,79]

In order to use the data for parameterization of the model, the following pre-processing was performed. As the model requires a finer resolution than the given data some assumptions had to be made as well.

- Assumption: Age and sex are (approximately) independent parameters
  - Calculated total number of diabetes cases per age cohort and sex based on marginal distributions
- Assumption: Total case numbers behave approximately linearly with time
  - Total numbers for cases linearly inter/extrapolated based on data for 2010 and 2030.
- Assumption: Diabetes cases are homogenously spread among Italy (i.e. Veneto cases can be scaled using the Veneto/Italy fraction)
  - Divided Population-numbers for Veneto by Italy (per year and sex gained from EUROPOP2013). Used this fraction to get case numbers for Veneto
- Diabetes cases per person (or per 10000) is a number that behaves linearly with age.
  - Gain diabetes cases per person for age cohorts [0,20) and [80+] by linear extrapolation from the other three available age classes [20,40), [40,60),[60,80). Finally gained total number of diabetes cases by re-multiplying these numbers with the population.

5. RESULTS

The results are clustered into developed methodological level and the problem solving results gathered using the model and scenario calculations.

5.1. Methodological findings and practical use

The GEPOC model mainly developed for use in Austria within the DEXHELPP consortium is tested to be flexible enough to integrate longer time spans and being parameterized for foreign countries.

During the calibration process a new method for agent based model parameter estimation has been developed (see extra papers in press from main author Martin Bicher) dealing with the problem of long cycle times for single simulation runs and therefore the necessity of fast converging algorithms.

The combination of expert knowledge of different disciplines – especially data scientists, medical doctors with background knowledge on real world treatment, statisticians and modelling experts – has been tested and methods toolkits (available under cephos-link.org) for international claims data usage in the psychiatric disease setting have been performed.

5.2. Simulation results

The results of the simulation scenarios in a aggregated form for 10-years age groups and mapped with the ppp cost data are analysed and depicted exemplarily in Figure 7 for the three countries/regions in parallel and for different age groups of Austria in Figure 8.

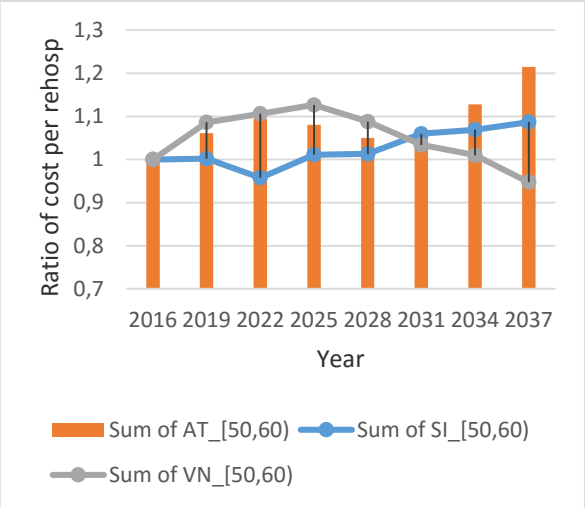

Figure 7: Relative change of the overall costs for re-hospitalizations for the age group of the 50 to 59 years old patients in the three regions in comparison. In each country the costs are inflation affected with the inflation of each country based on the year 2016.

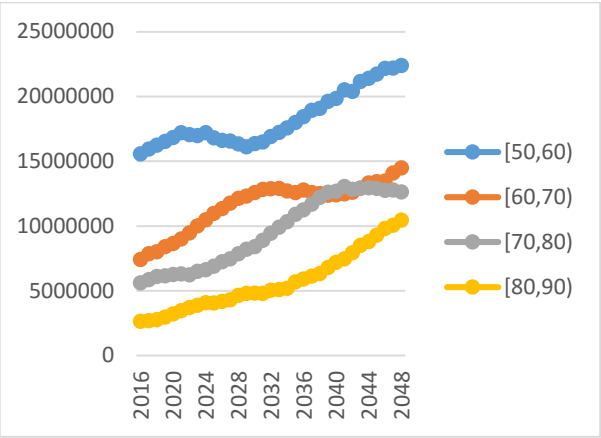

Figure 8 The graph represents the change over the whole simulation time for the Austrian data setting of the overall re-hospitalization costs for the four 10 years age groups between 50 and 90 years based on the Austrian inflation assumption.

6. DISCUSSION

All three scenarios show that psychiatric hospitalizations are rising, especially in Austria and Veneto. The most drastic changes can be assumed to come in the timeframe of the next 10 years for non-psychotic diagnosis.
Testing changes on treatment structures like distance to services and calculating corresponding what-if scenarios also provides more insight on effects of these interventions. Changing diabetes prevalence also has an impact on psychiatric patients' re-hospitalisation and shows that comorbidities should not be neglected when analysing future development of re-hospitalisation rates.

To gain more detailed results, the developed model provides a profound basis for integration of further modules. It is well suited for the implementation of patient pathways through the system, following their multiple re-hospitalisations as well as ambulatory treatment. For planning and testing new treatment strategies and/or structural changes, the simulation model can be extended, in order to assess the impact of such interventions and therefore, to optimize their implementation for different restrictions, like ethical or budget limits. Different expert opinions and can be tested in scenarios and the effect identified in testing regions can be expanded to the whole computer based test environment.
Altogether, we conclude that the model works well for the defined questions, but to improve prognosis quality further data and especially assumptions on causal relations are desirable. The implementation of the agent-based approach in the modular design for the CEPHOS-LINK model is flexible enough to suffice these further requirements and with improved data quality as well as more actual data provide can provide more insight on the development of both index- and re-hospitalisation rates.
The parameterization of the model shows that the countries share similar properties from a qualitative point of view which is in itself an interesting result. It shows that although there are quantitative differences the countries probably share the same causal relations in the background which lead to hospitalisation and re-hospitalisation rates.
An interesting part for future model based evaluations is therefore integration of even more interdisciplinary knowledge also from social sciences, experts on plans of changing treatment infrastructure and different guidelines. Utilizing such a simulation model correctly then may prevent unexpected treatment bottlenecks and help decision makers to optimize allocation of their resources for better treatment of psychiatric patients.

ACKNOWLEDGMENTS
This study was funded as part of the CEPHOS-LINK (Comparative Effectiveness Research on Psychiatric Hospitalization by Record Linkage of Large Administrative Data Sets) within the 7th framework program for research, grant agreement number 603264.
The K-Project DEXHELPP as part of COMET – Competence Centres for Excellent Technologies - is sponsored by BMVIT, BMFW and the city of Vienna. The COMET project is organized by FFG.

REFERENCES
Aslam S, Emmanuel P. Formulating a researchable question: A critical step for facilitating good clinical research. *Indian Journal of Sexually Transmitted Diseases*. 2010;31(1):47-50.

Bicher, M., B. Glock, F. Miksch, G. Schneckenreither, and N. Popper. 2015. "Definition, Validation and Comparison of Two Population Models for Austria". In Book of Abstracts, 4th International Conference on Business, Technology and Innovation 2015. Durres, Albania: UBT - Higher Education Institution.

Bicher, M., and N. Popper. 2016. "Mean-Field Approximation of a Microscopic Population Model for Austria". In Proceedings of the 9th EUROSIM Congress on Modelling and Simulation, 544–545. Oulu, Finland.

Breitenecker F., Miksch F., Popper N., Urach C., Weisser A., 2011. Dealing with Health Care Data of the Austrian Social Security System. Medical Decision Making, 31 (1), E51.

Donisi V, Tedeschi F, Wahlbeck K, Haaramo P, Amaddeo F. "Pre-discharge factors predicting readmissions of psychiatric patients: A systematic review of the literature" BMC Psychiatry, 16:449, 2016.

Kalton A., E. Falconer, J. Docherty, D Alevras, D. Brann, K. Johnson, Multi-Agent-Based Simulation of a Complex Ecosystem of Mental Health Care. Journal of Medical Systems. 2016.

Silverman, B.G., Hanrahan, N., Bharathy, G., Gordon, K., Johnson, D.: A systems approach to healthcare: Agent-based modeling, community mental health, and population well-being. Artificial Intelligence in Medicine 63(2), 61–71 (2015)

Sprah, L, M Z Dernovsek, K. Wahlbeck, and P. Haaramo. 2017, December. "Psychiatric readmissions and their association with physical comorbidity: a systematic literature review". BMC Psychiatry 17 (1).

Taboada M, E Cabrera, F Epelde, M L Iglesias, E Luque, Using an Agent-based Simulation for Predicting the Effects of Patients Derivation Policies in Emergency Departments, Procedia Computer Science, Volume 18, 2013, Pages 641-650

Urach, C., G. Zauner, K. Wahlbeck, P. Haaramo, and N. Popper. 2016, Dec. **"**Statistical methods and modelling techniques for analysing hospital readmission of discharged psychiatric patients: a systematic literature review". BMC Psychiatry 16 (1).

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SIMULATION OF NEW-BORNS BEHAVIOURS DURING CARDIO-PULMONARY RESUSCITATION

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ABSTRACT
This research concerns the formulation of a methodology and its application to elaborate conceptual models of pathological new-borns behaviours combined with the cardio-pulmonary resuscitation gestures. The methodology follows an experimental approach based on the analysis of academic documents, operating experience documents, and practitioner interviews. The implemented process consisted in adopting approach and methods from Cognitive Engineering in order to elaborate an ontology as a basis for the development of conceptual models of the resuscitation scenarios as well as the specification of a simulator. The process is based on the knowledge engineering method, KOD. The formalization of the conceptual models consisted in integrating the concepts into the definition of classes and objects and, by the use of a discrete event formalism. As a result, a simulator has been built to train medical practitioners to face situations, which are reported to potentially cause errors and thus improve the safety of the resuscitation gestures.

Keywords: new-borns resuscitation, simulation, conceptual modelling, ontology engineering

1. INTRODUCTION

"Approximately 10% of newborns require respiratory support at birth and 1% require complex resuscitation" (ILCOR 2006). In France, 25% of the causes of neonatal mortality are due to respiratory difficulties: intra-uterine hypoxia, asphyxia at birth, respiratory distress syndrome or other respiratory diseases.
Given these emergencies at birth, specialized technical equipment and skilled personnel are required to carry out all or part of the following sequence of actions (ILCOR 2006): (i) the initial stage of stabilization (airway clearance, neonatal placement and stimulation), (ii) ventilation, (iii) chest compressions, and (iv) medication or volume expansion.
These actions are well known and quite simple to perform. The criticality of these situations is due to time constraints and the fact that these are not routine situations. Medical personnel have to analyse the situation, diagnose the problem and perform the "right" actions within the minute after birth. A diagnostic or performance error can lead to irreversible damage or death. The problem is that despite the rarity of these situations, they require highly trained medical personnel.
The project "Cyber-Poupon", developed in partnership with Ab Initio Medical, is to propose an answer to this problem of qualification. It consists in designing and developing an integrated simulation system for the training of hospital staff who may be confronted with the critical situations of resuscitation of new-borns.
The main instrumented anatomical simulators of new-borns are marketed by the companies Laerdall, Simulaids and Meti. They all contain a large number of configurable physiological functions and most pathological behavioural scenarios of the new-born. These simulators are now widely used in resuscitation training centres. However, there are still many gaps that can interfere with learning objectives:

- Lack of realism in physical appearance (materials, resemblance)
- The lack of realism of the dynamic aspect (behaviour, movements, reactivity)
- The non-automatic evaluation of the learner's gestures (reaction of the new-born to resuscitation actions).

These inadequacies necessarily induce behaviours of the learner too far from what he must master in real situations. These shortcomings have led the reponsibles in charge of the neonatology service to develop their own simulation system, in relationship with the Ab Initio Medical company and the "Laboratoire des Sciences de l'Information et des Systèmes".
The current work lies in the following research fields: (1) from the medical field perspective, the paper presents a software tool (simulator) to train medical

staff to cardio-pulmonary resuscitation gestures to improve new-borns safety and (2) from a methodological perspective, the paper shows the importance of developing ontologies (i) for structuring a domain (at a conceptual level) as its actors perceive it and (ii) for using these ontologies to build computer tools with pedagogical perspective in that domain.
An overview of the Cyber-Poupon project is presented in Section 2 and Section 3 describes the methodological approach and the process used to build the Simulator. In the Section 4 the implementation of the process is developed and exemplified. Section 5 presents the conclusions.

2. THE CYBER-POUPON PROJECT

The "Cyber-Poupon" project consists of developing a realistic simulation system designed to train hospital agents to the resuscitation gestures of new-borns suffering from cardiopulmonary pathologies. The simulation system reproduces the different pathological behaviours of a new-born (New-Borns Simulator), the working environment of a resuscitation room (Resuscitation Environment Simulator), and a monitoring and control environment of the learner by a teacher (Monitoring and Control System) (Figure 1).
Two categories of exercises are possible: (i) targeted training on one or more specific gestures (intubation, ventilation, etc.) or (ii) training in the diagnosis of a pathology, followed by planning a Protocol and its implementation.
In the first class of exercises, the professor chooses the gesture (s) to be executed (1), in the second class of exercises the professor chooses a scenario corresponding to a pathology (1). In both cases, the simulator automatically generates the gesture reference model (2) as well as the Cyber-Poupon behaviour model (3). The comparison between the reference model of the gestures to be realized and the way they are actually performed produces a gap whose sign and amplitude will induce a new state of the Cyber-Poupon. This state is returned to the learner by visualizing physiological variables such as SPO2 or heart rate (4). The learner then adjusts his gestures (5) according to his analysis of this feedback. The teacher, through his Monitoring and Control system, receives the same information as the learner and can act directly on the learner's monitoring system (6). A set of cameras records the learner's work session as the basis for the debriefing session following the simulation session.
The simulation system belongs to the category of "Instrumented Anatomical Simulator" in reference to the classification of medical simulators proposed by (Silveira 2004):

- virtual simulators with a 3D Graphical User Interface (3D GUI);
- virtual simulators with a 3D GUI and coupled to a force feedback system;
- anatomical simulators consisting of a non-instrumented dummy;
- Instrumented Anatomical Simulators (IAS).

The IAS simulators consist of an instrumented dummy ("New-Borns Simulator" - Figure 1) and can be supplemented by a virtual interface ("Resuscitation Environment Simulator" and "Monitoring and Control System" - Figure 1). They are recognized to provide a more realistic immersion of the learners.

3. METHODOLOGICAL APPROACH

3.1. Analysis of the problem

One of the main problems arising during the conception of new computing tools, and more accurately for computing tools with pedagogical objectives is linked to the right transmission of the right system of concepts. A failed transmission or a wrong system of concepts can lead to “dormant faults” for learners which will became active within the critical situations of the resuscitation and could lead to fatal accidents for new-borns.
The notion of ontology and works currently developed by the scientific community of the knowledge engineers can bring interesting answers to this problem. One of the objectives of ontology is to facilitate the exchanges of knowledge between human beings, between human beings and machines as well as between human beings through machines (Uschold 1996).
The advantages in developing ontologies to solve problems arising in the field of safety and Health care are the following: (i) they structure the domain in highlighting concepts and semantic relations that are linking these concepts, (ii) they can be used to be the base for new computer tool design, and (iii) new pedagogical approaches. Tools so built are carrying knowledge shared by the actors of the domain, what makes them more effective to train medical staff to the right gestures within critical situations.
The followed methodological process (Figure 2) consists in adopting approach and methods from Cognitive Engineering in order to elaborate an ontology as a basis for the development of conceptual models of the resuscitation scenarios as well as the specification of a simulator. The process is based on the "Knowledge Oriented Design” (KOD) method (Vogel 1988; Mercantini 2007). KOD was designed to guide the knowledge engineer in its task of developing knowledge based systems. This method was designed to introduce an explicit model between the formulation of the problem in natural language and its representation in the formal language chosen. The inductive process of KOD is based on the analysis of a corpus of documents, speeches and comments from expert domain, in such a way to express an explicit cognitive model (also called conceptual model).

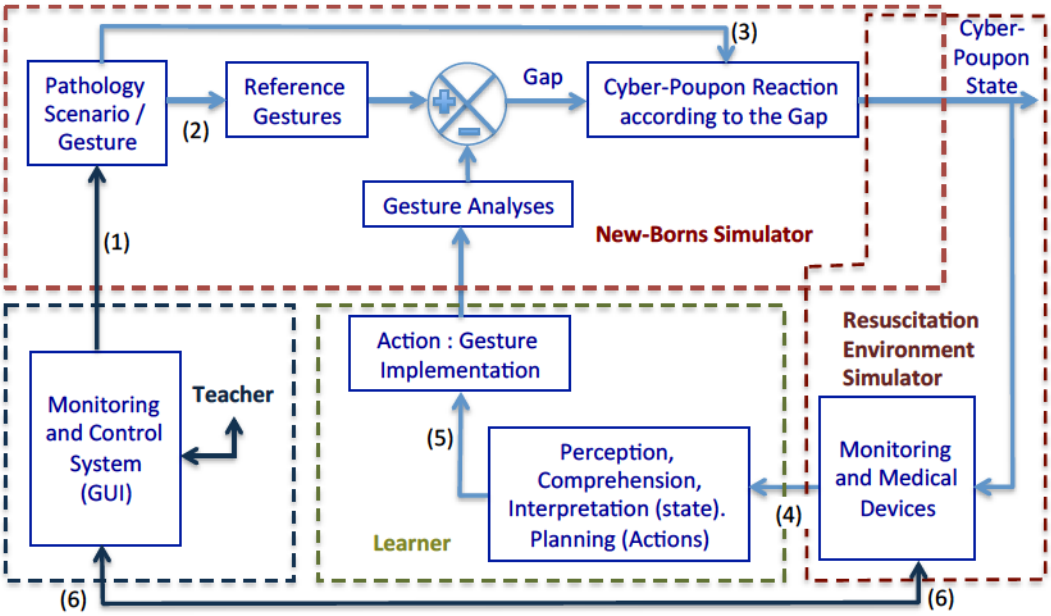

Figure 1: Functional diagram of the new-borns simulation system (the Cyber-Poupon project). Relationships labelled with a number between brackets (n) are detailed in the paragraph: "The Cyber-Poupon project".

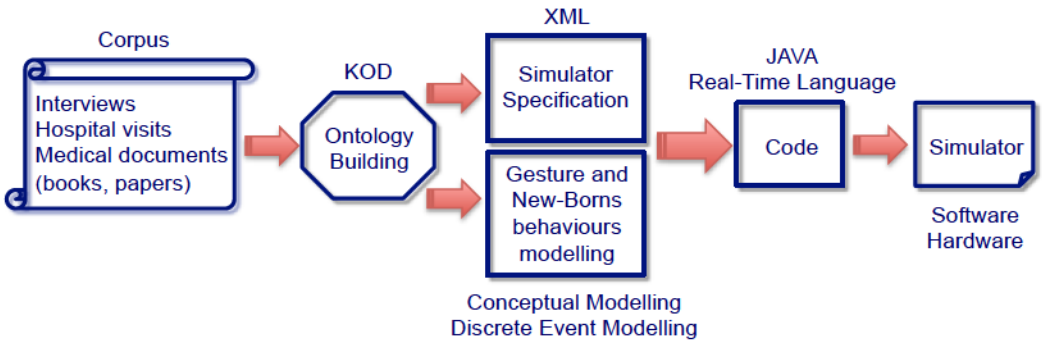

Figure 2: The implemented methodological approach for the Cyber-Poupon project.

Table 1. KOD, the three modelling levels.

Paradigms / Models	Representation	Action	Interpretation
Practical	Taxeme: object static representation	Acteme: dynamic representation of active objects	Inferences
Cognitive	Taxonomy: object static organization according to theirs properties	Actinomy: dynamic object organization	Reasoning Pattern
Software	Classes	Methods	Rules

ISBN 978-88-97999-89-8; Bruzzone, Frascio, Longo and Novak Eds.

3.2. The KOD method

KOD is based on an inductive approach requiring to explicitly express the cognitive model (or the conceptual model) based on a corpus of documents, comments and experts' statements. The main features of this method are based on linguistics and anthropological principles. Its linguistics basis makes it well suited for the acquisition of knowledge expressed in natural language. Thus, it proposes a methodological framework to guide the collection of terms and to organize them based on a terminological analysis (linguistic capacity). Through its anthropological basis, KOD provides a methodological framework, facilitating the semantic analysis of the terminology used to produce a cognitive model (conceptualisation capacity). It guides the work of the knowledge engineer from the extraction of knowledge to the development of the conceptual model.

The implementation of the KOD method is based on the development of three successive models: the practical models, the cognitive model and the software model (Table 1). Each of these models is developed according to the three paradigms: <Representation, Action, Interpretation / Intention>.

The Representation paradigm gives the KOD method the ability to model the universe such as experts represent it. This universe is made of concrete or abstract objects in relation. The KOD method provides methodological tools to develop the structure of this universe of knowledge according to this paradigm. The Action paradigm gives the KOD method the ability to model the behaviour of active objects that activate procedures upon receipt of messages. Thus, the action plans designed by human operator, as well as those of artificial operators, will be modelled in the same format. The Interpretation / Intention paradigm gives the KOD method the capability to model the reasoning used by experts to interpret situations and elaborate action plans related to their intentions (reasoning capacity).

The practical model is the representation of a speech or document expressed in the terms of the domain, by means of "taxemes" (static representation of objects – French word), "actemes" (dynamic representation of objects – French word) and inferences (base of the cognitive reasoning pattern). A "taxeme" is a minimum grammatical feature; it is the verbalisation of an object or a class of objects. An "acteme" is the verbalisation of an act or a transformation, a unit of behaviour. An inference is the act or process of deriving logical conclusions from premises known or assumed to be true. The cognitive model is constructed by abstracting the practical models. The cognitive model is composed of taxonomies, actinomies and reasoning patterns. The software model results from the formalization of a cognitive model expressed in a formal language independently of any programming language.

3.3 The ontology building process using KOD

Research work in Ontology Engineering has put in evidence five main steps for building ontologies (Dahlgren 1995; Uschold 1996; Fernández-López 1999; Aussenac-Gilles 2000; Gandon 2002):

1. *Ontology Specification*. The purpose of this step is to provide a description of the problem as well as the method to solve it. This step allows one to describe the objectives, scope and granularity size of the ontology to be developped.
2. *Corpus Definition*. The purpose is to select among the available information sources, those that will allow the objectives of the study to be attained.
3. *Linguistic Study of the Corpus*. It consists in a terminological analysis of the corpus in order to extract the candidate terms and their relations. Linguistics is specially concerned to the extent that available data for ontology building are often expressed as linguistic expressions. The characterization of the sense of these linguistic expressions leads to determine contextual meanings.
4. *Conceptualization*. Within this step, the candidate terms and their relations resulting from the linguistic study are analyzed. The candidate terms are transformed into concepts and their lexical relations are transformed in semantic relations. The result of this step is a conceptual model.
5. *Formalization*. The step consists in expressing the conceptual model by means of a formal language.

The projection of the KOD method on the general approach for developing ontology shows that KOD guides the corpus constitution and provides the tools to meet the operational steps 3 (linguistic study) and 4 (conceptualization) (Table 2). Under previous researches, the KOD method has been already implemented (Mercantini 2003; Mercantini 2004; Mercantini 2007; Mercantini 20015) in the domains of road safety, safety of urban industrial sites and study of conduct errors of industrial plants.

Table 2: Integration of the KOD method into the elaboration process of ontology

Elaboration process of Ontology	KOD process	Elaboration process of ontology with KOD
1. Specification		1. Specification
2. Corpus definition		2. Corpus definition
3. Linguistic study	1. Practical Model	3. Practical Model
4. Conceptualisation	2. Cognitive Model	4. Cognitive Model
5. Formalisation		5. Formalisation
	3. Software Model	6. Software Model

4. ELABORATION OF THE ONTOLOGY

4.1. Ontology specification

The KOD method does not offer tools facilitating the specification of ontology. To carry out this step, many authors recommend the use of the concept of scenario (Uschold 1996; Caroll 1997; Gandon 2002) with the objectives to clarify and justify the validity of building ontology, the future uses and the future addressees. We do not further develop this stage but we illustrate it by giving summaries of the scenario that have been drafted within the framework of the triplet Td: <Domain, Problem, Method>.

The domain is that of the new-borns cardio-pulmonary resuscitation. The problem is to train medical staff to produce the right diagnosis, the right gesture planning and the right gesture execution. The problem solving method consists in the elaboration of a cooperative system of simulation.

4.2. Corpus Definition

Definition and analysis of the corpus are performed on the basis of the specification of the ontology as well as the consideration of the properties of practical and conceptual models resulting from the application of the KOD method. Thus, the documents to be collected must be both representative of the triplet <Domain, Problem, Method> and meet the criteria of suitability required by the three paradigms <Representation, Action, Interpretation / Intention>. The combination of the triplet (Td) with the three paradigms constitutes a helpful grid to analyse the ontology specification with the goal to define the documents that must constitute the corpus.

The types of documents that make up this corpus are the following:

- Professional documents about medical protocols,
- Academic documents about the resuscitation gestures,
- Technical documents about the main Instrumented Anatomical Simulators of new-borns,
- Interviews concerning the return on operating experience about well done resuscitation,
- Interviews concerning the return on operating experience about erroneously done resuscitation.

4.3. Practical models

This step consists in extracting from each document of the corpus, all the elements (objects, actions, and inferences) that are relevant to the representation of pathological new-borns behaviours combined with the cardio-pulmonary resuscitation gestures.

4.3.1 Extracting taxemes

The linguistic analysis is performed in two steps: the verbalization and the modelling. The verbalization step consists in paraphrasing the corpus documents in order to obtain simple phrases, which allow qualification of the terms employed during document analysis. Some terms appear as objects, others appear as properties, and yet others appear as relations between objects and values. The modelling step consists of representing the phrases in the format of taxeme: <object, attribute, value>.

The taxeme characterizes an object from the real world by means of a relation (attribute), which links the object to a value. There are five types of relations: classifying (is-a, kind-of), identifying (is), descriptive (position, failure mode, error mode, cause, etc.), structural (composed-of) and situational (is-in, is-below, etc.). The example that follows illustrates the process employed to obtain the taxemes in the case of the bag mask ventilation gesture. Extracted and translated from (Lavaud 2004):

"... Two types of manual insufflators are presented: AMBU type and Laerdal type. ..."

"…The AMBU manual insuflator is made of: the balloon, injection and exhalation valves, the pressure relief valve, the universal patient connector, and the oxygen connection. …"

Paraphrases:

1. The "AMBU manual insufflator" is a manual insufflator
2. The "Laerdal manual insufflator" is a manual insufflator
3. The "AMBU manual insufflator" is made of a balloon
4. The "AMBU manual insufflator" is made of an injection valve
5. The "AMBU manual insufflator" is made of an exhalation valve
6. Etc.

Taxemes:

1. <AMBU manual insufflator, *kind-of*, Manual insufflator>
2. < Laerdal manual insufflator, *kind-of*, Manual insufflator >
3. < AMBU manual insufflator, *composed-of*, Balloon>
4. < AMBU manual insufflator, *composed-of*, Injection valve >
5. < AMBU manual insufflator, *composed-of*, Exhalation valve >
6. etc.

The extent of this analysis at the Corpus, have allowed obtaining the set of taxemes needed for the

representation of the universe described by the corpus of documents. An object of the real world is modelled by the sum of the related taxemes.

4.3.2 Extracting actemes

In order to obtain the actemes, the linguistic analysis consists on identifying verbs that represent activities performed by actors during resuscitation or object behaviour. In general terms, an activity is performed by an action manager, by means of one or more instruments, in order to modify the state (physical or knowledge) of the addressee. The action manager temporarily takes control of the addressee by means of instruments. Occasionally the action manager can be one who directs the activity and at the same time is also subjected to the change of state (example: knowledge acquisition). The following example illustrates how to extract actemes from the Corpus: "... The manual bag mask ventilation is carried out by means of a manual insufflator by exerting repeated compressions of the balloon (50 cycles per minute for the new-born and 30 cycles per minute for the infant ..."
The activity (or action) is "Manual Bag Mask VENTILATION". Once identified, the activity is translated into a 7-tuple (the acteme):

<Action Manager, Action, Addressee, Properties, State1, State2, Instruments>

Where: the Action Manager performs the action (the Learner); the Action causes the change; the Addressee undergoes the action (the Cyber-Poupon); the Properties represent the way the action is performed; State 1 is the state of the addressee before the change; State 2 is the state of the addressee after the change; Instruments, is one or a set of instruments representing the means used to cause the change (the insufflator).
The acteme "Manual Bag Mask VENTILATION" is represented as following:

<Learner, Manual Bag Mask VENTILATION, Cyber-Poupon, (Cycles per minute, Regularity, duration), Cyber-Poupon (not ventilated), Cyber-Poupon (ventilated), AMBU Manual Insufflator>

Actemes can be represented according to an actigram form (Figure 3) or to a table form (Figure 4).

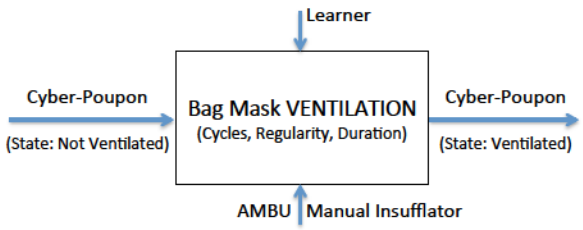

Figure 3: Representation of the Acteme "Bag Mask VENTILATION" according to an actigram form.

Action: Bag Mask VENTILATION	
Components	**Values**
Action Manager	{Learner, Professor}
Addressee	{Cyber-Poupon}
Addressee State1	{Not Ventilated}
Addressee State2	{Ventilated}
Instruments	{AMBU Manual Insufflator, Leardal Manual Insufflator}
Properties	{Cycles, Régularity, Duration}

Figure 4: Representation of the Acteme "Bag Mask VENTILATION" according to a table form.

The state of the Cyber-Poupon summarized in Figures 2 and 3 by the terms "Not Ventilated" and "Ventilated" is in fact modelled by the following set of attributes (state variables):

- SPO2 (partial pressure of oxygen in the blood),
- Heart rate,
- Respiratory Frequency,
- Blood pressure,
- Colour,
- Tonicity,
- Screams.

The values of each attribute (state variable) evolves according to the right or wrong realization of the considered action: the "bag Mask Ventilation" in the case of the example.
Actemes model resuscitation activities. An Acteme is composed of textual items extracted from corpus documents, which describe the state change of an object as described by the domain experts. Each element of the 7-tuple must be previously defined as a taxeme.

4.4. The cognitive model

This phase consists of the analysis and abstraction of the Practical Models. The objective is to build the application ontology. In other words, the aim is to classify the used terminology and thus obtain the KOD Cognitive Model

4.4.1 Taxinomy building

Taxinomy building is based on term analysis and concept identification.
Term analysis consists in solving problems induced by homonym and synonym terms, with the objective to build a common terminology.
Concept Identification is based on the analysis of taxemes and consists in highlighting the nature of attributes, which characterize each object. The attribute nature is the basis for the construction of the taxonomies (relations 'kind-of' and 'is-a') or other tree type structures (relations: 'is-composed-of', 'position', 'is-in', 'is-below', 'is-above', etc.).

According to the previous example, it is possible to construct the taxonomy of the Manual Insufflators (*kind-of* relation – Figure 5), and a tree structure giving the composition of an AMBU Manual Insufflator (*Composed-of* relation – Figure 6). All the taxemes of the corpus have been organized in taxonomies and tree structures to express all the relationships between concepts.

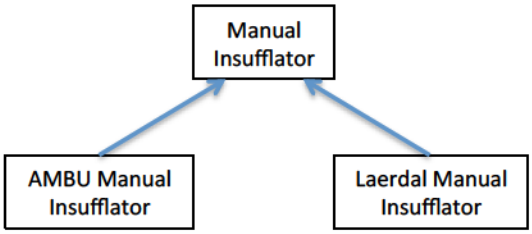

Figure 5: Taxonomy of Manual Insufflators. "*kind- of*" relation.

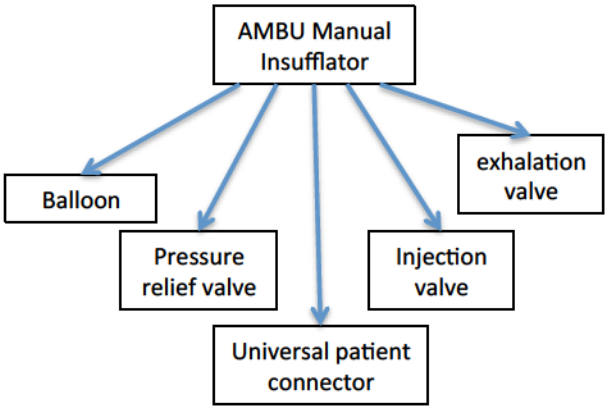

Figure 6: Tree structure with the "*Composed-of*" relation.

4.4.2. Actemes abstraction

One result of the acteme analysis is that actemes can be devided into three main action categories:

- Actions related to new-borns behaviours,
- Actions related to resuscitation gestures,
- Actions related pedagogical services.

Amongst actions related to new-borns behaviours we can cite: Tonicity change, Heart Rate (HR) change, SPO2 change, etc. Amongst actions related to resuscitation gesture, we can cite: Manual Bag Mask Ventilation, Nasotracheal Intubation, Tracheal aspiration, Gastric emptying, Heart massage, etc. The actions related to pedagogical services are implemented to improve the simulator functionalities such as: recording a simulation session, inserting comments during a simulation session, etc.

The actemes abstraction has led to two kinds of organization: action taxonomies and actinomies. As an example, Figure 7 presents the taxonomy of the Ventilation actions. Some actemes of the resuscitation gesture can be organized in a structural and temporal way to form actinomies. The interest of this kind of structure is that actions are already planned and they can be used as a reference model (Figure 8).

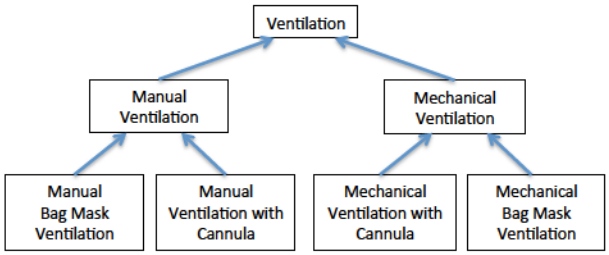

Figure 7: Extract of the resuscitation gestures taxonomy centred on the Ventilation gesture ("*kind-of*" relation).

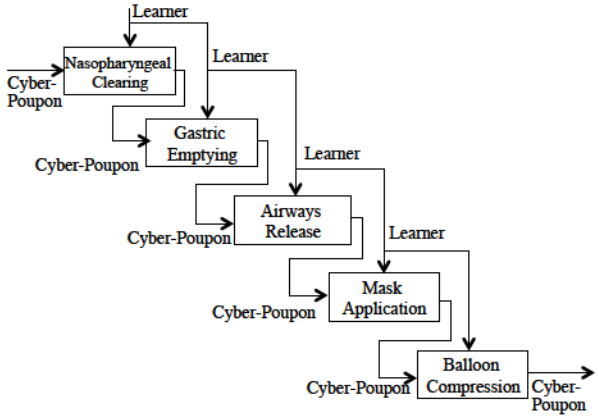

Figure 8: Simplified representation of the "Manual Bag Mask VENTILATION" actinomy.

4.4.2. Building of Reasoning Patterns

The modelling in the form of inferences consists in representing the elements of the corpus that characterize the cognitive activities of humans or machines.

Inferences are the basic elements of the Interpretation / Intention paradigm. An inference is the mental process, which consists in drawing a conclusion from a series of propositions accepted as true (premises).

To illustrate this step of the methodology process, an extract of the new-borns behavioural analysis has been chosen. In this study, the Interpretation addresses observations of physiological situations of new-borns, and the Intention concerns planning of "pseudo-physiological" discrete states. Premise propositions are resulting from the interpretation of the situation elements. They are obtained from observation and therefore, they are held to be true. The conclusion is related to "pseudo-physiological" state transitions.

A detailed presentation of this step is not permitted due to confidentiality. The presentation will be limited to the final rules on the thresholds triggering the transitions of pseudo-physiological states and not on the laws and rules defining the evolution of the physiological variables according to gestures.

The new-borns behaviours have been modelled by means of six discrete states where State0 is the "normal state" and State5 is the death. The state transitions are

relative to the values of two physiological variables: the SPO2 and the Heart Rate (HR).

IF (HR >150 and Spo2 > 75) THEN State = State0; (Normal)
IF (HR ∈]105 ; 150] and Spo2 ∈]65 ; 75]) THEN State = State1;
IF (HR ∈]60 ; 105] and Spo2 ∈]30 ; 65]) THEN State = State2;
IF (HR ∈]30 ; 60] and Spo2 ∈]20 ; 30]) THEN State = State3;
IF (HR ∈]0 ; 30] and Spo2 ∈]0 ; 20]) THEN State = State4;
IF (HR = 0 and Spo2 = 0) THEN State = State5; (Death)

The resulting new-borns behaviour, for the ventilation gesture, is modelled by the state-chart diagram of the Figure 9. The state-chart evolves according to two types of transitions: the transitions related to the crossing of certain thresholds for the SPO2 and Heart Rate variables, and the transitions relative to the time spent in a state (δint) without improvement of the physiological variables.

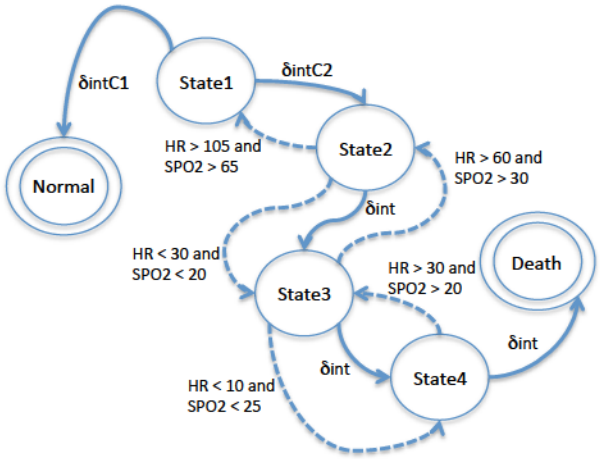

Figure 9: State-chart diagram modelling the new-borns behaviour according to the right or wrong execution of the ventilation gesture.

5. CONCLUSION

The paper presents the methodology process implemented to develop a system of simulation to train medical practitioners to the resuscitation gestures. The process is based on building an application ontology used to elaborate conceptual models of the new-borns behaviours and resuscitation gestures, and to specify the system of simulation. The Manual Bag Mask Ventilation gesture has been used to exemplify the implementation of the process. In the present state of realization of the system of simulation, nasotracheal intubation and cardiac massage have also been analysed, modelled and coded completely.

This work showed that the use of an application ontology was relevant to ensure the consistency of the modelling and specification processes since both use the same stabilized vocabulary. Furthermore, the ontology structures the domain (new-borns resuscitation) according to the problem to solve (training medical staff) and to the problem solving method (simulation). The ontology was obtained through a cognitive approach, which consisted in applying the KOD method, which has proven to be adequate.

The simulation system including learners and professors management, simulation sessions and debriefing sessions was performed. Three resuscitation gestures are currently available. Future works concern the development of the other resuscitation gestures as well as the final robot of the new-born.

REFERENCES

Aussenac-Gilles N., Biébow B. and Szulman S., 2000. Revisiting Ontology Design: a method based on corpus analysis. EKAW-2000, Proceedings of the 12th International Conference on Knowledge Engineering and Knowledge Management, R. Dieng et O. Corby (éd.), LNAI 1937, Springer, pp. 172-188.

Caroll J.M., 1997. Scenario-Based Design. In M. Helander, T.K. Landauer, P. Prabhu (Ed.), *Handbook of Human-Computer Interaction* (Chapter 17). Second completely revised edition, Elsevier Science B.V.

Dahlgren, K., 1995. A Linguistic Ontology. International Journal of Human-Computer Studies, vol. 43, n°5, pp. 809-818.

Fernández-López M., 1999. Overview of methodologies for building ontologies. Proceedings, IJCAI-99 Workshop on Ontologies and Problem-Solving Methods (KRR5), pp. 4-1 to 4-13. August 2, 1999. Stockhom, Sweden.

Gandon F., 2002. Ontology engineering: a survey and a return on experience. Research Report n° 4396. INRIA Sophia-Antipolis, mars 2002.

ILCOR, (2006). The International Liaison Committee on Resuscitation (ILCOR) Consensus on Science With Treatment Recommendations for Pediatric and Neonatal Patients: Neonatal Resuscitation. In PEDIATRICS 2006 (Official Journal of the American Academy of Pediatrics) ; 117 ; e978 ; originally published online April 17, 2006; DOI: 10.1542/peds. 2006-0350.

Lavaud J., Ayachi A., 2004. Réanimation et transport pédiatriques. Book, 5th Edition, Editions Masson.

Mercantini J.-M., Capus L., Chouraqui E., Tourigny N., 2003. Knowledge Engineering contributions in traffic road accident analysis. In: Ravi K. Jain, Ajith Abraham, Colette Faucher, Berend Jan Van der Zwaag, eds. Innovations in Knowledge Engineering. pp 211-244.

Mercantini J.-M., Turnell M.F.Q.V, Guerrero C.V.S, Chouraqui E., Vieira F.A.Q et Pereira M.R.B, 2004. Human centred modelling of incident scenarios. IEEE SMC 2004, Proceedings of the International Conference on Systems, Man & Cybernetics, pp. 893-898. October 10-13, The Hague, The Netherlands.

Mercantini JM., Tourigny N., Chouraqui E., 2007. Elaboration d'ontologies à partir de corpus en utilisant la méthode d'ingénierie des connaissances KOD. 1ère édition des Journées Francophones sur

les Ontologies (JFO 2007), n° ISBN : 978-9973-37-414-1, pp 195-214, 18 – 20 Octobre 2007, Sousse (Tunisie).

Mercantini J.-M., 2015. Building a domain ontology to design a decision support software to plan fight actions against marine pollutions. In: Springer-Verlag, Risk and Cognition, Mercantini JM. and Faucher C. (Editors). Intelligent Systems Reference Library, Vol. 80, January 2015.

Silveira R.C., 2004. Modélisation et conception d'un nouveau simulateur d'accouchement (BirthSim) pour l'entrainement et l'enseignement des jeunes obstétriciens et des sages femmes. PhD Thesis, Institut National des Sciences Appliquées de Lyon (INSA), December 6, 2004.

Uschold M. and King M., 1995. Towards a Methodology for Building Ontologies. Proceedings of the IJCAI-95 Worshop on Basic Ontological Issues in Knowledge Sharing, Montréal (Canada).

Uschold M. and Grüninger M., 1996. Ontologies: Principles, methods and applications. Knowledge Engineering Review, volume 11, n° 2, 1996, pp. 93-136.

Vogel C., 1988. Génie cognitif, Paris, Masson (Sciences cognitives).

THE MEDICAL POINT OF VIEW INTO A SIMULATION PROJECT OF MANAGEMENT FOR SAFETY AND SECURITY IN DISASTERS AND EMERGENCIES OF INDUSTRIAL PLANTS (DIEM-SSP PROJECT).

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ABSTRACT
Industrial mass casualty incidents are an unfortunate reality in the 21st century, but there are few situational training exercises to prepare and to cope with emergencies management. The Authors realized a project to carry out development of the activities devoted to face the complexities arising from emergencies in industrial plants. The DIEM-SSP is a simulation project working on two interoperable simulators, based on the IEEE 1516 High Level Architecture (HLA), used as test-bed on specific case studies. The project is aimed to study innovative emergency procedures and proper routing of critical patients with severe traumas toward the most suitable first aid facilities. The project takes into account the emergency procedures considering the human factor and the possibility of mistakes. It is aimed to test and validate these methodologies through a test-bed based on distributed and interoperable simulation. The Authors report the medical contribution in this project.

Keywords: medical and surgical simulation, emergency management, triage, pre-hospital disaster.

1. INTRODUCTION

The emergency can be caused: by a fault of a system, by a human error or by natural factors (Meshkati 1995).
Hospitals play a critical role in providing communities with essential medical care during all types of disasters. Any accident that damages systems or people often requires a multi-functional response and recovery effort. Without an appropriate emergency planning, it is impossible to provide good care during a critical event.
In fact, during a disaster condition could occur patients with the same "critical" severity. Thus, it is essential to categorize and to prioritize patients with the aim to provide the best care to as many patients as possible with the available resources. Triage assesses the severity of patients to give an order of medical visit (Frascio, Mandolfino, Zomparelli and Petrillo 2017).
Aspects such as the definition of proper emergency procedures to be carried out in healthcare facilities, or directly in the emergency site, the assessment of their impact on the performance of such structures, the proper handling of injured people, the optimal healthcare facilities location and the human errors reduction must be duly taken into account.
Indeed a critical aspect in emergency management is related to the efficiency of first aid facilities. It is critical to have accurate symptoms assessment and quick decision-making to match critical patient needs. Real-time points-of-care, based on new approaches/methodologies, i.e. ultrasound, are the real added value for the assessment of critical patients both in pre-hospital and in in-hospital situations. Although recommendations in term of education and decision making have been proposed by a variety of specialties, to date they are still scattered and limited examples of standards for critical and intensive care professionals.
Efficient procedures are needed both on the emergency site and in hospitals; these procedures should be combined with a proper critical patients routing toward the most suitable first-aid facilities and with a reduction of human errors during the emergency management. Furthermore, new procedures or methodologies for emergency management must be carefully tested before being used: the need to assess their validity before their application in a real emergency situation depends on the need to have a clear picture of the procedures effectiveness.

2. SIMULATION

Simulation represents a good tool to check human and structures reaction to a stressing and challenging situation.
Simulation-based education is an important training strategy in emergency medicine postgraduate programs (Russell, Williamson, Bartko and Bradley 2005).
Simulation has been used successfully to train learners to provide acute care (Harris, Adler, Unti and McBride

2017).
Models for advanced and realistic patient simulation driven by intelligent agents is the solution in the educational programs for health students enabled by new technologies (Bruzzone, Frascio, Longo, Siri and Tremori 2012).
A simulation based evaluation methodology provides a fair framework to assess the effectiveness of models and we may obtain interesting insights and results from such an analysis.
It is worth saying that in such a context, any new emergency procedure or methodology needs to be extensively tested and validated before use. To this end, simulation has been widely recognized as the most suitable approach for investigating, analyzing and solving complex problems in real systems such as industrial plants and Critical Infrastructures (CIs).
The available literature clearly states that simulation can be effectively used for emergency management, even if much more can be done by using interoperable and distributed simulation, e.g. by using architecture for distributed simulation such as HLA.
In this case different interoperable simulation models, recreating the behaviour of different entities acting in the same scenario, could represent a useful simulation model.
It is expected a model able to recreate the evacuation process and the critical patients routing to first aid facilities and a simulation model recreating the emergency procedures.
According on previous positive experience of simulation in medicine, two interoperable simulators, based on the IEEE 1516 HLA, have been developed and used as test-bed on specific case studies, to get benefits from interoperable simulation, in federating multidisciplinary models for industrial plant emergency management.
Modern simulation, by using technology enables such as mobile solution, enhance its support to first responders, the dynamic reaction to crisis evolution as well as the improvement in training and management of safe routing and handling of injured people (Bruzzone, Frascio, Longo, Petrillo and Carotenuto 2014).

3. THE PROJECT

In this scenario it has been thought and realized the project DIEM-SSP, to carry out research and development activities, devoted to face the complexities that arise from emergencies management in industrial plants and CIs.
The goals of the DIEM-SSP project can be summarized:

1. Definition and study of innovative emergency procedures, that must be used within first aid facilities for critical patients, coming from the place where the emergency has occurred, suffering from severe traumas.
2. Proper routing of critical patients with severe traumas toward the most suitable first aid facilities, that must be detected through a study on the optimal infrastructures location and the design of the logistic network.
3. Reduction of the number of patients with severe traumas and the damages to critical infrastructures or industrial plants, through innovative emergency procedures, that take into account the human factor, namely its reliability and the possibility of mistakes.
4. Test and validation of these methodologies through a test-bed based on distributed and interoperable simulation.

4. THE MEDICAL POINT OF VIEW

The medical team job has to be focused on the study and analysis of the actual standard hospital pathway followed by severely injured patients, in order to identify critical issues and possible improvements.
Beginning from the selection of referent professionals involved in critical scenarios management (intensivists, surgeons, emergency doctors, anesthetists), the Authors have performed an assessment of the diagnostic resources habitually used by the emergency clinicians.
This activity was aimed at identifying and defining clinical performance indicators and outcomes to be used for evaluating the goodness of the procedures used.
The evaluation of the impact of the procedures used on the technical efficiency of the hospital has been evaluated by using the DIEM-SSP simulators.
To handle any emergencies that are created, it is necessary to develop a proper plan in order to respond to emergencies.

4.1. Advanced Medical Post

The term Advanced Medical Post (AMP) is referred to a medical station, sited in an area close to the disaster but in a safety zone, where the disaster casualties are cared and selected.
The organization of an advanced medical post can be improved on a strategic level to increase rescue quality, including enhanced survival of injured victims (Rauner, Schaffhauser-Linzatti and Niessner 2012).
The AMP provides different functions: to collect the victims, to concentrate the first aid resources, to perform the triage, to treat the injured people with life-saving maneuvers, to manage the ambulance transport of injured subjects in the most suitable hospitals.
The AMP could be of two levels (Gazzetta Ufficiale della Repubblica Italiana 2007):

- First level AMP, aimed to a limited disaster, able to treat about 30 yellow/red codes and expected for 12 hours of autonomous activity.
- Second level AMP, aimed to cope natural or catastrophic disaster, able to treat independently about 150 yellow/red codes and expected for 72 hours of autonomous activity.

The rescue pre-hospital procedures could be identified in three phases:

1. The triage of victims.
2. The first aid and stabilizing the injured people.
3. The medical activity into the AMP with re-evaluation of triage, first medical aid for critical subjects and the discharge of the victims to be transported to the nearby hospitals.

4.2. The Triage

Triage is one of the most important management and decision-making concepts in emergency wards and disasters (Pouraghaei 2017; Lindsey 2005; Turris 2012; Halpern 2012).

There are two sub-categories of triage, namely hospital and pre-hospital triage. (Cross 2013; Risavi 2001; Aylwin 2005; Dadashzadeh 2011; Göransson 2011).

Generally, when there is an overflow of patients in the emergency ward of hospitals or when there are numerous casualties and injured people at the accident scene, triage is the only way of developing the maximum facility for the maximum number of patients (Fry 2001; Sauer 2009; Lerner 2008; Andersson 2006; Twomey 2007)

One of the most important phases is the response phase, that addresses immediate threats presented by the disaster, including saving lives, also meeting humanitarian needs, and the start of resource distribution. In this phase a particular process involves the triage efforts that aims to assess and deal with the most pressing emergency issues. This period is often marked by some level of chaos, a period of time that cannot be defined a priori, since depend on the nature of the disaster and the extent of damage (Caunhye 2012).

It is necessary to assess the conditions of the patients during the response phase and to reduce waiting time for medical services and transport (Hamm 1997). A timely and quickly identification of patients with urgent, life-threatening conditions is needed (Buckle 1999). Accurate triage is the “key” to an efficient operation and to determine severity of illness or injury for each patient who enters the emergency department (Christ 2010).

The term triage comes from the French verb trier, meaning to separate, sift or select.

A system for classification of patients was first used by Baron Dominique Jean Larry, a chief surgeon in Napoleon’s army (Burris 2004). Originally, the concepts of triage were primarily focused on mass casualty situations. Many of the original concepts of triage remain valid today in mass casualty and warfare situations. Triage is a dynamic and complex decision making process (Bullard 2008).

In general, patients should have a triage assessment within 10 minutes of arrival in the emergency department in order to ensure their proper medical management. But, it is not always possible to achieve this purpose. Some weaknesses characterize every triage models. It is worthy to underline that exist several methods of triage for evaluating the condition of a patient and treat him/her accordingly. The triage methods most commonly used are: Australasian triage scale, the Canadian Triage and Acuity Scale, Manchester Triage System and Emergency Severity Index. Each protocol may be very different from another in terms of methods of care, treatments and strategies (Lerner 2008). Furthermore, the medical staff has to analyze several factors to decide in which hospital the patient should properly be conducted (Andersson 2006). The effective triage is based on the knowledge, skills and attitudes of the triage staff. However, despite this knowledge it is evident that the use of one triage algorithm is limited (Twomei 2007; Australasian College for Emergency Medicine 2000; Considine 2004).

The critical trauma patient has only 60 minutes, the “golden hour”, from the time of injury to reach definitive surgical care or the odds of a successful recovery diminish dramatically.

4.2.1. The Triage of DIEM-SSP project

We proposed the START SYSTEM: S (simple) T (triage) A (and) R (rapid) T (treatment).

It is one of the triage systems widely accepted and used to manage disasters, first applied in the US in the 1983.

START was developed by the Newport Beach Fire and Marine Department and Hoag Hospital in Newport Beach, California in 1983.

Initially it used the ability to obey commands, respiratory rate, and capillary refill to assign triage category.

Modifications to START in 1996 substituted radial pulse for capillary refill, with a report of improved accuracy, especially in cold temperature.

The Benson revision START-SAVE (Secondary Assessment of Victim Endpoint), also incorporates additional factors that determine "survivability" over time, as the event progresses and assumes limited response resources (Benson 1996).

There has been limited rigorous scientific review of various forms of mass casualty incident triage used around the world (Garner 2001; Jenkins 2008; Cone 2005)

New methods of triage using new algorithms have been proposed, but not tested in the field.

At present START remains the most commonly used mass casualty triage algorithm in the US.

In other words, START was done at the scene of unexpected incidents in a preliminary fashion and involves passing alongside some casualties who died; hence attempts are merely directed towards people who have a higher chance of survival (Armstrong 2008).

We preferred the START system even if, as other quick triage protocols, it has some limitations including negligence of the injury mechanism, limited assessment, and failure to monitor patients with a mild or moderate injury, whose transfer is delayed (Neal 2010; Kahn 2009; Healey 2003).

The criteria used to triage patient in a mass casualty incident, as in the DIEM-SSP project is expected, differ to traditional In-Hospital Triage (IHT).

The traditional IHT is based on severity, usually completed by nurses, the sickest patient are seen first, many resources may be dedicated to save one critical patient and detailed hystory can be collected and assessment completed.
But when the number of casualties overcome resources the triage is heavily determined by available resources, it can be done by any member of emergency team.
Critical patients may not receive treatment.
Disaster triage implies that the most seriously injured may be relegated to the end of the line and left untreated, even at risk of death, if their care would absorb so much time and attention that the work of rescue would be compromised. This is one of the few places where a "utilitarian rule" governs medicine: the greater good of the greater number rather than the particular good of the patient at hand. This rule is justified only because of the clear necessity of general public welfare in a crisis (Jonsen 1998).
The START-SAVE triage was developed to direct limited resources to the subgroup of patients expected to benefit most from their use. The SAVE assesses survivability of patients with various injuries and, on the basis of trauma statistics, uses this information to describe the relationship between expected benefits and resources consumed. Pre-existing disease and age are factored into the triage decisions. As an example: an elderly patient with burns to 70% of body surface area is unsalvageable under austere field conditions and would require the use of significant medical resources-both personnel and equipment and would be triaged to an "expectant area." Conversely, a young adult with a Glasgow Coma Scale score of 12, who requires only airway maintenance, would use few resources and would have a reasonable chance for survival with the interventions available in the field, and would be triaged to a "treatment" area. The START MDR-SAVE methodology is the first systematic attempt to use triage as a tool to maximize patient benefit in the immediate aftermath of a catastrophic disaster (Benson 1996).

4.2.2. START Adult Triage Algorithm

Here is reported a synthesis of the START adult algorithm (Benson 1996). Four distinct clinical triage categories for mass casualty patients, with each category assigned a distinct name and colour.
The 4 Triage Categories are:

- Minor: Green Triage Tag Colour, which comprehends: victim with relatively minor injuries, status unlikely to deteriorate over days, patient may be able to assist in own care: also known as "walking wounded".
- Delayed: Yellow Triage Tag Colour, which comprehends: victim's transport can be delayed, includes serious and potentially life-threatening injuries, but status not expected to deteriorate significantly over several hours.
- Immediate: Red Triage Tag Colour, which comprehends: victim can be helped by immediate intervention and transport, requires medical attention within minutes for survival (up to 60 minutes), includes compromise to patient's airway, breathing, and circulation (the ABC's of initial resuscitation).
- Expectant: Black Triage Tag Colour, which comprehends: victim unlikely to survive given severity of injuries, level of available care, or both, palliative care and pain relief should be provided.

How this information would be used in a mass casualty event:

- Emergency first clinical responders would follow the clinical algorithm to evaluate each patient and assign a triage category and color based on various clinical parameters.
- The information would be noted on the triage tag attached to the mass casualty victim.
- Rescuers following after the triage officer would view the color and text of the triage tag and take appropriate action.

Clinical parameters used to evaluate patients include:

- Ability to walk.
- Presence or absence of spontaneous breathing.
- Respiratory rate greater or less than 30 per minute.
- Perfusion assessment using either the palpable radial pulse or visible capillary refill rate.
- Mental status as assessed by ability to obey commands.

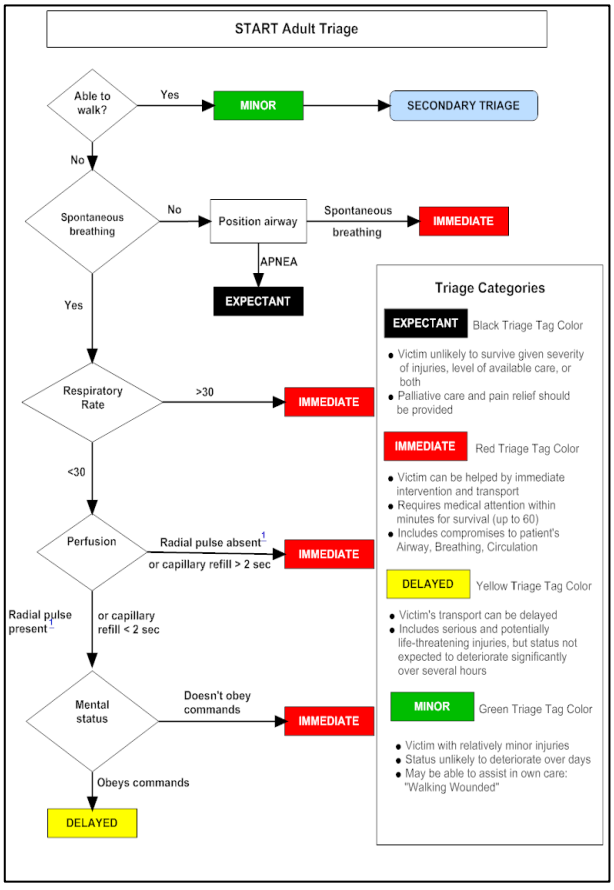

Figure 1: the START Triage Algorythm

ISBN 978-88-97999-89-8; Bruzzone, Frascio, Longo and Novak Eds.

ACKNOWLEDGMENTS

This research represents a result of research activity carried out with the financial support of MIUR, namely PRIN 2012 "Disasters and Emergencies Management for Safety and Security in industrial Plants".

REFERENCES

Andersson A.K., Omberg M., Svedlund M. 2006. Triage in the emergency department – a qualitative study of the factors which nurses consider when making decision. Nursing in critical care. 11 (3), 136-145.

Armstrong J.H., Frykberg E.R., Burris D.G. 2008.Toward a national standard in primary mass casualty triage. Disaster Medicine Public Health Preparedness. 2 (Suppl 1), S8–S10.

Australasian College for Emergency Medicine, 2000. Guidelines on the implementation of the Australasian triage scale in emergency department. Guideline Document No G24, Version No V24. Available from: https://acem.org.au [accessed 5 April 2017]

Aylwin C.J., König T.C., Brennan N.W., Shirley P.J., Davies G., Walsh M.S. 2006. Reduction in critical mortality in urban mass casualty incidents: analysis of triage, surge, and resource use after the London bombings on July7, 2005. Lancet. 368 (9554), 2219–25.

Benson M., Koenig K.L., Schultz C.H. 1996. Disaster triage: START, then SAVE-a new method of dynamic triage for victims of a catastrophic earthquake. Prehospital Disaster Medicine. 11 (2), 117-124.

Bruzzone A.G., Frascio M., Longo F, Siri A., Tremori A. 2012. MARIA: An agent driven simulation for a web based serious game devoted to renew education processes in health care. Proceedings of 1st International Workshop on Innovative Simulation for Health Care, IWISH. Held at the International Multidisciplinary Modelling & Simulation Multiconference, pp. 188-194. September 19-21. Wien (Austria).

Bruzzone A.G., Frascio M., Longo F., Petrillo A., Carotenuto P. 2014. Disaster and emergency management simulation in industrial plants. Proceedings of 26th European Modeling and Simulation Symposium, EMSS pp. 649-656. September 10-12. Bordeaux (France).

Buckle P. 1999. Re-defining community on vulnerability in the context of emergency management. Australian Journal of Emergency Management. 198 (5), 831-835

Bullard M.J., Unger B., Spence J., Grafstein E. 2008. Revision to the Canadian Emergency Department Triage and Acuity Scale (CTAS) adult guidelines. Canadian Journal of Emergency Medicine. 10 (2), 136-151.

Burris M. J., Wellin D.R., Rich N.M. 2004. Dominique Jean Larrey and the principles of humanity in warfare. Journal of American College of Surgeons. 198 (5), 831-835.

Caunhye A.M., Nie X., Pokharel S. 2012. Optimization models in emergency logistics: A literature review. Socio-Economic Planning Sciences. 46 (1), 4-13.

Christ M., Grossman F., Winter D. 2010. Modern triage in the emergency department. Deutsches Arzteblat. 107 (50), 892-898

Cone D.C., Koenig K.L. 2005. Mass casualty triage in the chemical, biological, radiological, or nuclear environment. European Journal of Emergency Medicine. 12 (6), 287-302.

Considine J., Le Vasseur S.A., Villanueva E. 2004. The australasian triage scale: examining emergency deparment nurses' performance using computer scenarios. Annals of Emergency Medicine. 44 (59), 516-523

Cross K.P., Cicero M.X., 2013. Head-to-head comparison of disaster triage methods in pediatric, adult, and geriatric patients. Annals Emergency Medicine, 61(6), 668-676.

Dadashzadeh A., Abdollahzadeh F., Shams Vahdati S., Lotfi M., Ghojazadeh M., Bagheri Mehmandousti S. 2011. Causes of delay in patient triage in the emergency departments of tabriz hospitals. Triage Journal Emergency Medicine. 11 (3), 95–8.

Frascio M., Mandolfino F., Zomparelli F., Petrillo A., 2017, A cognitive Model for emergency management in Hospital: proposal of a triage severity index. In: De Felice F., Petrillo A., eds. Theory and application on cognitive factors and risk management–New trends and Procedures. Rijeka, Croatia: Intech, 1-18.

Fry M., Burr G. 2001. Current triage practice and influences affecting clinical decision-making in emergency departments in NSW Australia. Accident and Emergency Nursing. 9 (4), 227–34.

Garner A., Lee A., Harrison K., Schultz C.H. 2001. Comparative analysis of multiple-casualty incident triage algorithms. Annals of Emergency Medicine. 38 (5), 541-548.

Gazzetta Ufficiale della Repubblica Italiana. 2008. Direttiva del Presidente del Consiglio dei Ministri. 13 dicembre 2007 "Procedure e modulistica del triage sanitario nelle catastrofi". 17 aprile 2008 n. 91.

Göransson K.E., Von Rosen A. 2011. Interrupter agreement: A comparison between two emergency department triage scales. European Journal of Emergency Medicine. 18 (2), 68–72.

Halpern P., Goldberg S.A., Keng J.G., Koenig K.L. 2012. Principles of Emergency Department facility design for optimal management of mass-casualty incidents. Prehospital Disaster Medicine, 27 (2), 204-12.

Hamm C., Goldman B.U., Heeschen C. 1997. Emergency room triage of patient with acute chest pain by means of rapid testing for cardiac troponin T or troponin I. New England Journal of Medicine. 337 (23), 1648-1653

Harris T.H., Adler M., Unti S.M., McBride M.E. 2017. Pediatric heart disease simulation curriculum: Educating the pediatrician. Congenital Heart Disease, Jul, 12(4), 546-553.

Healey C., Osler T.M., Rogers F.B. 2003. Improving the Glasgow Coma Scale score: motor score alone is a better predictor. Journal of Trauma. 54 (4), 671–680.

Jenkins J.L., McCarthy M.L., Sauer L.M. 2008. Mass-casualty triage: time for an evidence-based approach. Prehospital Disaster Medicine. 23 (1), 3-8.

Jonsen A.R. and Edwards K., 1998. Resource Allocation. Ethics in Medicine, University of Washington School of Medicine. Available from: https://depts.washington.edu/bioethx/topics/resall.html [accessed 5 April 2017]

Kahn C.A., Schultz C.H., Miller K., Anderson C.L. 2009. Does START triage work? An outcomes-level assessment of use at a mass casualty event. Annals of Emergency Medicine. 4 (3), 424-430.

Lerner E.B., Schwartz R.B., Coule P.L., Weinstein E.S., Cone D. C., Hunt R.C. 2008. Mass casualty triage: an evaluation of the data and development of a proposed national guideline. Disaster Medicine and Public Health Preparedness. 2 (S1), 25–34.

Lindsey J. 2005. New triage method considers available resources. Journal of Emergency Medical Services. 30 (7), 92–94.

Meshkati N., 1998, Human factors in process plants and facility design. In: Deshotles R., Zimmerman R,, eds. Cost-Effective Risk Assessment for Process Design. New York, USA: Mc Graw Hill, 113-130.

Neal D.J., Barbera J.A., Harrald J.R. 2010. PLUS prehospital mass-casualty triage: a strategy for addressing unusual injury mechanisms. Prehospital Disaster Medicine. 25 (3), 227–36.

Pouraghaei M, Sadegh Tabrizi J., Moharamzadeh P., Rajaei Ghafori R., Rahmani F., Najafi Mirfakhraei B. 2017. The Effect of Start Triage Education on Knowledge and Practice of Emergency Medical Technicians in Disasters. J Caring Science. Jun 1,6 (2), 119-125.

Rauner M.S., Schaffhauser-Linzatti M.M., Niessner H. 2012. Resource planning for ambulance services in mass casualty incidents: a DES-based policy model. Health Care Management Science. Sept, 15 (3), 54-69.

Risavi B.L., Salen P.N., Heller M.B. 2001. A two-hour intervention using START improves prehospital triage of mass casualty incidents. Prehospital Emergency Care. 5 (2), 197–199.

Russell C.M, Williamson D.F, Bartko J.J, Bradley E.L., 1994. Simulation study of a panel of reliability indicators applied to paired measurements. American Journal Human Biology, 6 (3), 311-320.

Sacco W.J., Navin D.M., Fiedler K.E. 2005. Precise formulation and evidence-based application of resource-constrained triage. Academic Emergency Medicine.12 (8), 759–770.

Sauer L.M., McCarthy M.L., Knebel A., Brewster P. 2009. Major influences on hospital emergency management and disaster preparedness. Disaster medicine and public health preparedness. 3(S1), 68-73.

Turris S.A., Lund A., 2012. Triage during mass gatherings. Prehospital Disaster Medicine. 27 (6), 531-535.

Twomei M., Wallis L.A., Myers J.E. 2007. Limitation in validating emergency department triage scales. Emergency Medicine Journal. 24 (7), 477-479.

Twomey M., Wallis L.A., Myers J.E. Limitations in validating emergency department triage scales. Emergency Medicine Journal. 4 (7), 477–479.

GENERATOR OF DIETS FOR INDIVIDUALS WITH DIABETES WITH MINIMIZATION OF GLYCEMIC INDEX

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ABSTRACT
In the present paper, the concept of glycemic index of foods is taken as a measure for the dietary control of type 1 diabetes mellitus and it is included as an "objective function" in a linear programming model that will serve to generate a proposal of diet; it takes into consideration the energy requirements and the number of macronutrients (carbohydrates, proteins, and lipids). The linear programming model is based on "equivalent" food groups with standardized measures that, on average, have the same number of macronutrients, thus facilitating the exchange of food within each group. The flexibility of the model allows changes in the matrix of resources and constraints, generating scenarios for various diet proposals for different energy requirements based on a low glycemic index.

Keywords: Dietary control of type 1 diabetes mellitus, Glycemic index, Simulation, Optimization.

1. INTRODUCTION

Diabetes mellitus (DM), or simply diabetes, is a chronic disease that occurs when the pancreas is no longer able to make insulin, or when the body cannot make good use of the insulin it produces. Insulin is a hormone made by the pancreas, that acts like a key to let glucose from the food we eat pass from the blood stream into the cells in the body to produce energy. Carbohydrates (CH) are broken down into glucose in the blood. Insulin helps glucose get into the cells (International Diabetes Federation 2015). For this reason, a control of food intake is very important in people with DM.

Until recently, reducing fasting and pre-meal glucose levels was the basic approach to diabetes control. However, recent studies have shown that there is a strong relationship between high levels of glucose after meals (postprandial glucose) and the risk of diabetic complications (Ceriello and Colagiuri 2007).
People with diabetes are at increased risk of developing several serious health problems because of their inability to produce or use insulin effectively, which leads to elevated blood glucose levels (known as hyperglycemia). Eventually, high levels of glucose are associated with damage to the body and multiple organ and tissue insufficiencies (International Diabetes Federation 2015). Table 1 shows fasting and two-hour postprandial blood glucose levels; it helps assess if a person is healthy, if he or she has a higher risk of diabetes (prediabetes) or if he or she has the disease.

Table 1. Optimal Blood Sugar Levels Before and After two hours of Eating

Diabetic vs. Normal Blood Sugar Levels After Eating (Postprandial). By Diabalance.com			
Blood sugar classification	Fasting minimum [mg/dl]	Fasting maximum [mg/dl]	2 hours after eating [mg/dl]
Normal blood sugar	70	99	Less than 140
Pre-diabetes	100	125	140 to 199
Established Diabetes	Over 125	Over 125	More than 200

1.1. Glycemic Index

The term glycemic index (GI) was defined as the increase in the area under the blood glucose response curve obtained with 50 grams serving of carbohydrates available in a food, expressed as a percentage of the response, in the same subject, on the intake of 50 grams of anhydride glucose (Mateljan 2001).

Previously, most meal plans designed to improve blood sugar analyzed the total amount of carbohydrates (including sugars and starches) in the foods themselves. The GI goes beyond this approach, looking at the impact of foods on our actual blood sugar. In other words, instead of counting the total amount of CH in foods in their unconsumed state, GI measures the actual impact of these foods on our blood sugar. Therefore, the glycemic index is a systematic way of classifying CH based on their effect on the immediate increase on blood sugar

levels. Table 2 shows the ranges to classify food based on a low, medium or high glycemic index (Rakel 2008).

Table 2: Reference Ranges of Glycemic Index

Reference ranges Glycemic Index. By American Diabetes Association (2006).	
High glycemic index	70-100
Medium glycemic index	56-69
Low glycemic index	< 55

1.2. Justification

The glycemic index was conceived and communicated in 1981 by David Jenkins et al., At the University of Toronto Canada, as a weapon for the dietary management of Type 1 Diabetes Mellitus (T1DM). This value was more relevant to the glycemic control of diabetes by reducing the GI in the diet (Fontvieille et al., 1988, 1992; Brand et al., 1991; Frost et al., 1994). Numerous dietary data collected by D. Walter's group at Harvard University led to the publication of several papers that showed that a diet with a low GI reduced the risk of developing diabetes (Salmerón et al. 1997a, b).

GI is often criticized for its inability to reflect the glycemic effects of food when consumed in a mixture of foods because of added fats and proteins (Hollenbeck et al., 1986; American Diabetes Association 1994, 2002; Franz et al., 1994, 2002). However, the fact that GI is measured only in isolated foods is an important strength of the concept and that is precisely what allows GI to be useful. The point here is that GI is measured in individual foods and it is calculated for a mixture of foods (Wolever 2006).

The GI of the diet is determined by expanding the calculations made for the GI of a meal, that is:

$$\frac{\{\sum_{x}^{n=1} IG_n \times g_n\}}{G} \quad \ldots (\mathbf{A})$$

x: is the number of foods in a diet.

IG_n: is the glycemic index of each individual food.

g_n: are the grams of carbohydrates available in each individual food.

G: is the total carbohydrate available in the diet (in grams).

Given equation A (Wolever et al. 1994), to obtain the glycemic index of a diet, it is necessary to make the sum of the product between the IG_n and the grams corresponding to each individual food g_n and then divide that result among the total carbohydrates **G**.

2. MODEL FORMULATION

2.1. Data collection

The data and values were obtained from the food guide for the Mexican population and the Mexican system of equivalent foods (Pérez et al. 2014) and they were compared with the Mexican Official Standard NOM-015-SSA2-2010, for the prevention, treatment, and control of DM (Hernández 2016).

In normative appendix A, we can find the distribution of equivalents and estimate of daily energy requirements for people with diabetes. The number of equivalents varies per the energy requirements and these are calculated per the desirable weight, height, age, sex and physical activity of the individual.

2.2. Development of the model

For this model, the range of values present in the normative appendix A will be a useful basis for the generation of scenarios. So, one will have a minimum energy load of 1200 calories and a maximum load of 2500 calories. With these values, we have all the important considerations to formulate the linear programming model and to do the comparison of results and its validation.

2.3. Model construction

To obtain macronutrient restrictions (in grams) we used appendix A. The respective calculations were performed for each macronutrient, considering the distribution of equivalents.

Table 3: Name of the Model Variables

Variables by Secretaría de Salud, 2010.	
X1 = Cereals and Tubers without fat	X7 = Skimmed milk
X2 = Cereals and Tubers with fat	X8 = Whole milk
X3 = Vegetables	X9 = Leguminous plant
X4 = Fruits	X10 = Monounsaturated fats
X5 = Food of animal origin, very low in fat	X11 = Polyunsaturated fats
X6 = Food of animal origin, low in fat	X12 = saturated and trans fats

Objective function: Minimize the glycemic index of food in the diet.

$$\mathbf{Minz} = \mathbf{56X_1 + 63X_2 + 52X_3 + 49X_4 + 0X_5 + 0X_6 + 30X_7 + 28X_8 + 32X_9 + 0X_{10} + 0X_{11} + 0X_{12}} \quad \ldots (1)$$

S.T

$$66X_1 + 104X_2 + 22X_3 + 57X_4 + 40X_5 + 55X_6 + 95X_7 + 150X_8 + 112X_9 + 70X_{10} + 45X_{11} + 45X_{12} = (1200 - 2500) \quad \ldots (2)$$

$$14X_1 + 15X_2 + 4X_3 + 14X_4 + 0X_5 + 0X_6 + 12X_7 + 12X_8 + 19X_9 + 0X_{10} + 0X_{11} + 0X_{12} < 401 \quad \ldots (3a)$$

$$14X_1 + 15X_2 + 4X_3 + 14X_4 + 0X_5 + 0X_6 + 12X_7 + 12X_8 + 19X_9 + 0X_{10} + 0X_{11} + 0X_{12} > 172 \quad \ldots (3b)$$

$$1X_1 + 4X_2 + 0.2X_3 + 0.1X_4 + 1X_5 + 3X_6 + 2X_7 + 8X_8 + 1X_9 + 5X_{10} + 5X_{11} + 5X_{12} < 163$$
… (4a)

$$1X_1 + 4X_2 + 0.2X_3 + 0.1X_4 + 1X_5 + 3X_6 + 2X_7 + 8X_8 + 1X_9 + 5X_{10} + 5X_{11} + 5X_{12} > 31$$
… (4b)

$$2X_1 + 2X_2 + 1X_3 + 1X_4 + 7X_5 + 7X_6 + 9X_7 + 9X_8 + 7X_9 + 3X_{10} + 0X_{11} + 0X_{12} < 154$$
… (5a)

$$2X_1 + 2X_2 + 1X_3 + 1X_4 + 7X_5 + 7X_6 + 9X_7 + 9X_8 + 7X_9 + 3X_{10} + 0X_{11} + 0X_{12} > 73$$
… (5b)

$$1X_1 + 1X_2 + 2X_3 + 2X_4 + 6X_9 < 59$$
… (6a)

$$1X_1 + 1X_2 + 2X_3 + 2X_4 + 6X_9 > 16$$
… (6b)

$$X_i \geq 0, \qquad para\ i = 1, 2, 3 \ldots 12$$
… (7)

Where each equation represents:

Where each equation represents:

Objective function: Optimize (minimize) the glycemic index of available foods (1) (Navarro et al. 2016). Equation (2) refers to the calories present in said diet and varies from 1200 to 2500 of 100 in 100. The following equations refer to the restrictions in grams of maximum carbohydrates (3a) and minimum (3b), fats (4a) and (4b), proteins (5a) and (5b), fiber (6a) and (6b), and finally the non-negativity condition applied to each of the variables (7) is included.

Other restrictions included to improve the level of detail of the model are:

$$X_{10} + X_{11} + X_{12} < 6 \quad \ldots (8)$$

$$X_1 + X_2 > 5 \quad \ldots (9)$$

$$X_5 + X_6 < 8 \quad \ldots (10)$$

$$X_3 > 3 \quad \ldots (11)$$

$$X_4 > 3 \quad \ldots (12)$$

To increase the level of detail of the model, it was proposed to limit the consumption of lipids (8) and foods of animal origin (10). Also included were minimal amounts of some other foods such as fruits (12), vegetables (11), and cereals (9) that are indispensable for a balanced and healthy diet.

3. VALIDATION OF THE MODEL

To verify and validate the model, the results of the first run (with 1200 calories) are compared to the values in appendix A. The macronutrient values are calculated and compared with the model results.

Given appendix A, an amount of 3 equivalents of animal products, 1 milk equivalent, 1 legume, 5 vegetables, 5 cereals and tubers, and 3 servings of fruits are required for a 1200 calorie diet.

For the calculation of proteins, we have

$$Proteins = 3(7) + 9 + 8 + 5(2) + 5(2) + 5(3) = 73\ [gr]$$

$$Carbohydrates = 3(0) + 12 + 20 + 5(4) + 5(15) + 3(15) = 172\ [gr]$$

$$Lipids = 3(1) + 2 + 1 + 5(0) + 5(0) + 5(5) = 31\ [gr]$$

Table 4: Calculation of the GI of the meal considering the Distribution of Equivalents Recommended for Appendix A

Portions	GI of foods	Portion of carbohydrates	IG of the food mixture
5	63	44%	27
3	49	26%	13
5	52	12%	6
3	0	0%	0
1	32	12%	4
1	28	7%	2
5	0	0%	0
		1	**52**

And,

```
OBJECTIVE FUNCTION VALUE

1)       679.2641

VARIABLE        VALUE          REDUCED COST
      X1        5.000000          0.000000
      X2        0.000000         16.348791
      X3        3.000000          0.000000
      X4        3.000000          0.000000
      X5        0.000000          4.432940
      X6        4.434639          0.000000
      X7        0.673936          0.000000
      X8        1.132880          0.000000
      X9        1.385169          0.000000
     X10        0.000000         20.179493
     X11        0.000000          0.391765
     X12        0.000000          0.391765
```

Figure 1: Results of Model by Lingo

The macronutrients are calculated per the model.

$$Proteins = 5(2) + 3(1) + 3(1) + 4.43(7) + 0.67(9) + 1.13(9) + 1.38(7) = 73\ [gr]$$

$$Carbohydrates = 5(14) + 3(4) + 3(14) + 4.43(0) + 0.67(12) + 1.13(12) + 1.38(19) = 172\ [gr]$$

$$Lipids = 5(1) + 3(0.1) + 3(0.2) + 4.43(3) + 0.67(2) + 1.13(8) + 1.38(1) = 31\ [gr]$$

Table 5: Calculation of the GI of the diet resulting from the Model, Considering the Proportion of Carbohydrates Available for each Food

Portions	GI of foods	Portion of carbohydrates	IG of the food mixture
5	56	41%	23
3	49	24%	12
3	52	7%	4
4.43	0	0%	0
0.67	30	5%	1
1.13	28	8%	2
1.39	32	15%	5
		1	46.9

As shown in the above calculations, the amounts of macronutrients in the two cases are similar. Both the values calculated by the model results and those calculated based on appendix A are the same, although not all food groups are considered. Therefore, it can be said that the model presents realistic results and that, in addition, it will always comply with the criterion of minimization of the GI. With these results the model is validated.

4. RESULTS

To understand the results of the model, it was necessary to make use of several graphs, which are presented in figures 2, 3, 4 and 5.

Figure 2 shows the behavior of macronutrients in relation to energy requirements. Growth in protein and lipid amounts is observed. However, the amount of carbohydrates remains constant up to 2100 calories. This means that the model's priority is to stabilize the amount of carbohydrates to be consumed. One issue to keep in mind is that in order to optimize blood glucose levels, it is not necessary to decrease carbohydrate consumption, nor to abruptly increase the consumption of fats or proteins, since the values of the macronutrients are below the maximum values set as constraints in the model.

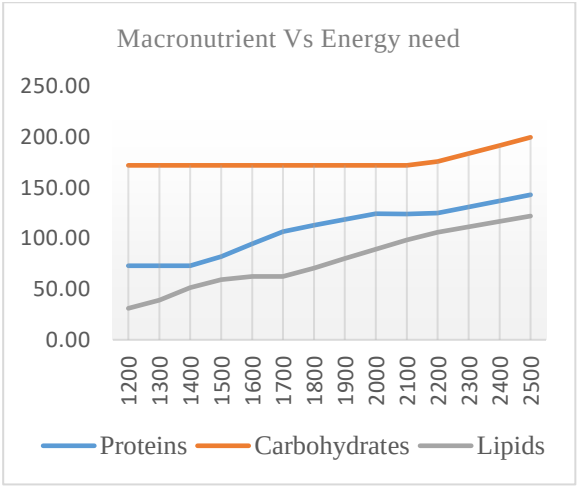

Figure 2: Behavior of Macronutrients in Relation to Energy Requirements

Figure 3 shows the behavior of the macronutrients (in percentages) with respect to the energy requirements. Compared with the previous figure, there is an almost linear decrease in the proportion of carbohydrates; this effect occurs because the consumption of carbohydrates (at least in quantity) remains constant while the amount of proteins and lipids continues to increase.

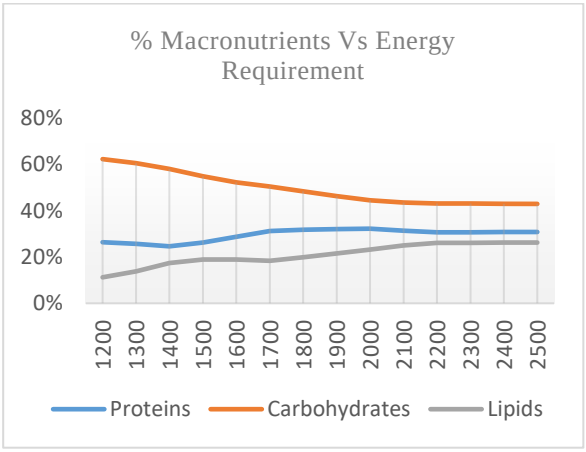

Figure 3: Percentage of Macronutrients by Energy Requirement

Figure 4 shows the way in which the model chooses the portions of foods per group (groups with no glycemic index are omitted). In this way, one can see how each food group will affect the glycemic index of the diet (the total food mix). For example, Figure 5 shows a peak (in the 2200 calories) in the glycemic index that is caused by the increase of the variables X8 (dairy) and X2 (cereals and tubers). Afterwards, a decrease is observed in the GI because the consumption of dairy products increases, while the consumption of cereals and tubers remains constant. If the values of the objective function are checked, they will realize that the glycemic index of X2 is greater than that of X8, that is, X2 has a medium glycemic index. This effect occurs because the consumption of foods with low glycemic indexes increases and (per the formula for calculating the GI of the meals) causes the total glycemic index to decrease.

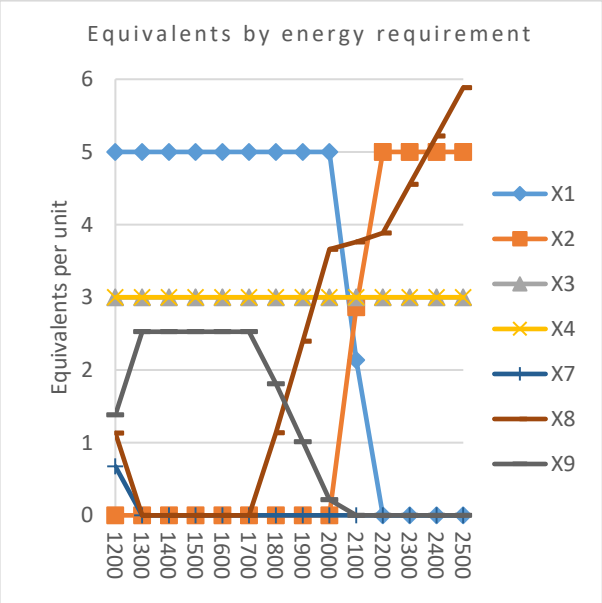

Figure 4: Behavior of the Equivalents (with sample of results for each group) with Respect to the Energy Requirements.

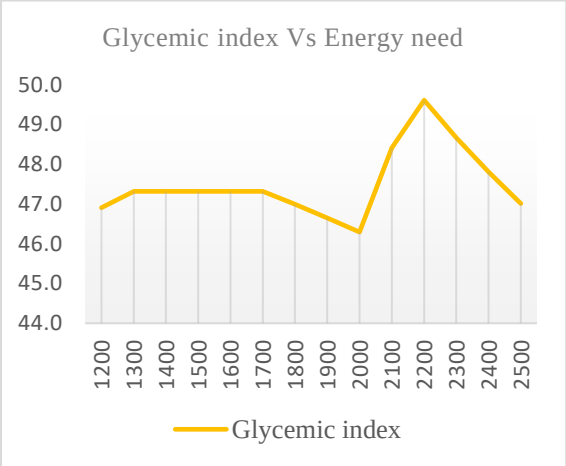

Figure 5: Behavior of Glycemic Index in Relation to Energy Requirements

5. CONCLUSIONS

It was possible to optimize the glycemic index of the proposed foods, since in calculating the GI of the proposed diet, the sum of the foods results in a low GI and the validity of the GI is verified when compared with the values of normative appendix A. However, the model would not make much sense without the correct method to calculate the GI of a food mixture, since there are other factors that could influence the glycemic impact of such a mixture, such as: the GI of each individual food, the total amount of carbohydrates available in the diet, and the proportion of carbohydrates per food. Factors that are considered in equation A.

The accuracy of the calculation of the GI of the diet depends on a good selection of data, since it makes use of food groups and the variation could affect the results. However, the values that were taken to obtain the model are based on standardized portions for each food group, which implies that foods have on average the same amount of carbohydrates, proteins and lipids, which facilitates the exchange of food within their respective group, obtaining a proposal of a varied and balanced diet, with a low glycemic index.

The viability of the proposed diets will be subject to the consideration and validation of a professional in nutrition, since in the calculation of the diets more factors intervene than those considered in the elaboration of the model, but it could easily be included as additional restrictions. This observation is made because a nutrition professional might consider that the model does not have a level of detail adequate enough to generate a real diet, because it could consider other factors that may modify macronutrient needs for each person. However, the level of detail that is achieved with the model serves to predict the behavior of macronutrients in the diet and facilitates the collection of certain indicators that could serve for a more qualitative measurement of the carbohydrates consumed in a diet. Finally, it is intended that this model serves as a tool in which these professionals can rely on to generate diets with low GI.

APPENDIX

NORMATIVE APPENDIX A

Distribution of equivalents in a meal plan for people with diabetes. By NOM-015SSA22010.						
Food group	1200 Kcal	1400 Kcal	1600 Kcal	1800 Kcal	2000 Kcal	2500 Kcal
Food of animal origin	3	4	5	5	6	8
Dairy products	1	2	2	2	2	3

Leguminous plant	1	1	1.5	2	2	2.5
Vegetables	5	5	5	5	5	7
Cereals and Tubers	5	5	6	6	6.5	7
Oils and Fats	5	5	5.5	6	6.5	7.5
Fruits	3	4	5	5	5	7

REFERENCES

Atkinson FS, Foster-Powell K, Brand-Miller JC., 2008. International Tables of Glycemic Index and Glycemic Load Values: 2008. Diabetes Care 31(12).

Brand, J.C., Colagiuri, S., Crossman, S., Allen, A., Roberts, D.C.K and Truswell, A.S., 1991. Low-glycemic index foods improve long-term glycemic control in NIDDM. Diabetes Care 14,95-101.

Ceriello, A., and Colagiuri, S., 2007. Guía para el control glucémico tras las comidas. Diabetes Voice 52(3), 9-11.

Fontvieille, A.M., Acosta, M., Rizkalla, S.W., Bornet, F., David, P., Letanoux, M., Tchobroustky, G. and Slama, G., 1988. A moderate switch from high to low glycaemic-index foods for 3 weeks improves the metabolic control of type I (IDDM) diabetic subjects. Diabetes Nutrition and Metabolism 1, 139-143.

Fontvieille, A.M., Rizkalla, S.W., Penfornis, M., Acosta, M., Bornet, F. and Slama, G., 1992. The use of low glycaemic index foods improves metabolic control of diabetic patiens over five weeks. Diabetic Medicine 9, 444-450.

Franz, M.J., Horton, E.S., Bantle, J.P., Beebe, C.A., Brunzell, J.D., Coulston, A.M., Henry, R.R., Hoogwerf, B.J. and Stacpoole, P.W., 1994. Nutrition principles for the management of diabetes and related complications. Diabetes Care 17, 490-518.

Franz, M.J., Bantle, J.P., Beebe, C.A., Chiasson, J.-L., Garg, A., Holzmeister, L.A., Hoogwerf, B., Mayer-Davis, E., Mooradian, A.D., Purnell, J.Q. and Wheeler, M., 2002. Evidence-based nutrition principles and recommendations for the treatment and prevention of diabetes and related complications. Diabetes Care 25, 148-198.

Frost, G., Wilding, J. and Beecham, J., 1994. Dietary advice based on the glycaemic index improves dietary profile and metabolic control in type 2 diabetic patients. Diabetic Medicine 11, 397-401.

Hernández A., Mauricio., 2016. NORMA Oficial Mexicana NOM 015-SSA2-2010, Para la prevención, tratamiento y control de la diabetes mellitus. Diario Oficial de la Federación. Available from: http://dof.gob.mx/nota_detalle.php?codigo=5168074&fecha=23/11/2010 [accessed 10 June 2016]

Hollenbeck, C.B., Coulston, A.M. and Reaven, G.M. 1986. Glycemic effects of carbohydrates: a different perspective. Diabetes Care 9, 641-647.

International Diabetes Federation, 2015. What is diabetes? IDF. Available from: http://www.idf.org/worlddiabetesday/toolkit/gp/what-is-diabetes [accessed 10 December 2016]

Jenkins, D.J.A., Wolever, T.M.S., Taylor, R.H., Barker, H.M., Fielden, H., Baldwin, J.M., Bowling, A.C., Newman, H.C., Jenkins, A.L. and Goff, D.V., 1981. Glycemic index of foods: a physiological basis for carbohydrate exchange. American Journal of Clinical Nutrition 34, 362-366.

Jenkins D, Wolever T. Jenkins. The glycaemic response to carbohydrate foods. Lancet 1984; II 388-391.

Mateljan, George., 2001. What is the Glycemic Index? International Diabetes Federation. Available from: http://www.idf.org/worlddiabetesday/toolkit/gp/what-is-diabetes [accessed 10 December 2016]

Navarro, M., Segura, E., 2016. Optimización de los niveles de glucosa en un paciente con diabetes mellitus tipo 1 mediante de un modelo de programación lineal. Proceedings of the XVIII Latin-Iberoamerican Conference on Operations Research, CLAIO 2016, 592-599. October 2, 2016, Pontificia Universidad Católica de Chile.

Pérez Lizaur A. B, Marván Laborde L. Palicios B. Sistema Mexicano de Alimentos Equivalentes. 3era. Ed. Fomento de Nutrición y Salud, A.C. México.

Rakel, David., 2008. Índice Glucémico y Carga Glucémica. University of Wisconsin http://www.fammed.wisc.edu/files/webfm-uploads/documents/outreach/im/handout_glycemic_index_patient_sp.pdf [accessed 10 December 2016]

Salmerón, J., Ascherio, A., Rimm, E.B., Colditz, G.A., Spiegelman, D., Jenkins, D.J., Stampfer, M.J., Wing, A.L. and Willet, W.C., 1997a. Dietary fiber, glycemic load, and risk of NIDDM in men. Diabetes Care 20, 545-550.

Salmerón, J., Manson, J.E., Stampfer, M.J., Colditz, G.A., Wing, A.L. and Willet, W.C., 1997b. Dietary fiber, glycemic load, and risk of non-insulin-dependent diabetes mellitus in women. Journal of the American Medical Association 277, 472-477.

Secretaría de Salud, 2010. Guía de alimentos para la población mexicana. Secretaría de Salud. SE.

Available from: http://www.imss.gob.mx/sites/all/statics/salud/guia-alimentos.pdf [accessed 10 December 2016]

Wolever, T.M.S., Nguyen, P.M., Chiasson, J.-L., Hunt, J.A., Josse, R.G., Palmason, C., Rodger, N.W., Ross, S.A., Ryan, E.A. and Tan, M.H., 1994. Determinants of diet glycemic index calculated retrospectively from diet records of 342 individuals with non-insulin-dependent diabetes mellitus. American Journal of Clinical Nutrition 59, 1265-1269.

Wolever, T.M.S., 2006. The Glycaemic Index A. Physiological Classification of Dietary Carbohydrate. CABI Publishing – a division of CAB INTERNATIONAL Wallingford, Oxon OX10 8DE, UK.

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HYPERBARIC PLANT SIMULATION FOR INDUSTRIAL APPLICATIONS

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ABSTRACT

Several industrials sectors require to extend underwater capabilities by adopting alternative and multiple solutions both involving human divers as well as robotic technologies such as ROVs & AUVs. In general the main mandate is to improve performance reducing costs and risks. On the other side, new technologies and advancements are enabling to further develop the potential of the above mentioned solutions; for instance the authors propose a new generation of computer based Hyperbaric Plant Simulators that are pretty promising for improving training & education without rising costs of underwater man based operations. This paper proposes an innovative approach in M&S for the Hyperbaric Plants devoted to support training and certification of Life Support Supervisors (LSS) as well as other operators active into diving activities.

Keywords: Hyperbaric Chamber Simulation, Underwater Operations, Life Support Supervisor

1 INTRODUCTION

Underwater activities carried out by humans or robotic systems are very important for many sectors especially Oil and Gas Industry; in facts there is an emergent request to carry out many activities such as maintenance and service of underwater installations, cables, pipelines in addition to marine salvage and rescue operations. The difficulties and risks associated to the underwater operations for human divers promoted the introduction of robotic solutions since almost 70 years, even if the performance of such systems were originally pretty limited and evolved drastically along last decades (Rebikoff 1954; Graczyk et al. 1970; Martin 2013). Despite the big advances offered by the new robotics systems, humans are still much more flexible in underwater operations where they could be active due to physiological limitations; indeed they provide higher productivity and they are still irreplaceable for completing some specific tasks; so due to these reasons the human divers are still in use along the years and their range of operations has been extended up to 250-300m (Naquet & Rostain 1988).

Therefore, the high deep operations are still very dangerous since are performed in an hostile environment for human health, characterized by high pressure, no breathable atmosphere, low temperature and total darkness. Due to these reasons very special equipment and pretty well trained personnel result fundamental for completing successful each mission. Indeed training plays a very important role in this sector, both for operations performed by human divers as well as for missions carried out by Remotely Operated underwater Vehicles (ROVs) or Autonomous Underwater Vehicles (AUVs) supervised by humans.

The training of new personnel is very critical because real operations are costly and dangerous, due to the risk of accidents, errors and mistakes of inexperienced people; in this context small errors involve big risks for human life, while the cost of carrying out the training at sea and/or by using real equipment is very expensive.

So, it is clear that modern M&S (Modeling and Simulation) could be very useful to support training activities, reduce costs and risks by substituting the real plant or equipment with a properly verified and validated simulator (Amico et al.2000). Currently the authors are involved in developing different simulators for this sector of applications, therefore in our paper the focus is on the creation of a simulation environment devoted specifically to train personnel involved in diving operations where the human intervention is required.

2 UNDERWATER OPERATIONS AND HYPERBARIC CHAMBERS

One of common techniques used in diving is Self-Contained Underwater Breathing Apparatus (SCUBA), which utilizes a breathing equipment carried entirely by a diver, however its application field is limited to shallow water, while in case of a deep waters, the saturation diving technique has to be applied (Department of the Navy 2005). Indeed, saturation diving is a technique that allows divers to stay and work at great depths for long periods of time; the term "saturation" refers to the fact that the diver's tissues are saturated with helium or other inert gas at the pressure of the surrounding water. In both civil and military fields a special hyperbaric chamber is necessary to perform all activities required by saturation diving techniques, which allows to extend the achievable deepness down to 300m, which represent the maximum depth safely affordable for human body.

In facts as the depth increases, it becomes necessary to use special breathing mixture due to the oxygen toxicity at high pressure. In general, it is necessary to replace the normal atmosphere composition with a special mixture consisting of an inert gas with reduced oxygen concentration respect to normal values.

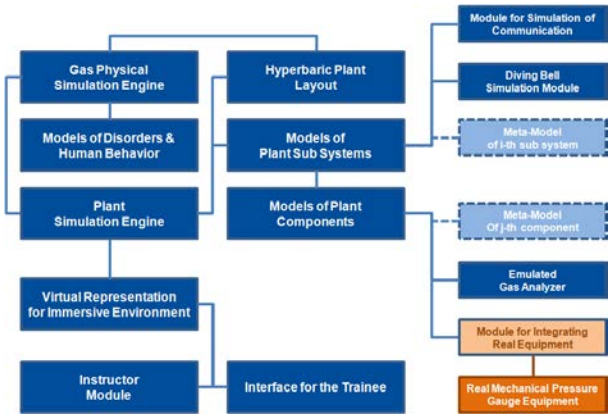

Figure 1 – General Architecture for Hyperbaric Chamber Simulation

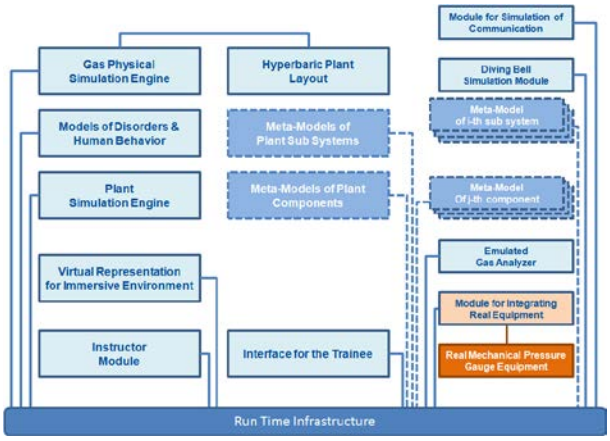

Figure 2 –Hyperbaric Chamber Simulation in HLA

Due to restrictions related to human body physiology, just for the decompression cycle, several days are required. This means that in Oil & Gas operations in deep waters, the hyperbaric chamber is part of a real plant that need to support the operations by covering many different aspects; for instance it is required a diving bell, plus pressure and gas mix control systems; in addition, due to normal operation requirements and economic consideration, the hyperbaric plant need to conduct long sessions lasting for weeks; indeed it is necessary to include within the hyperbaric plant all facilities and systems to provide life support, to host and to react to any possible crisis along its deployment on a ship or off-shore platform. In facts the hyperbaric chamber host normally multiple diver teams (often 3 teams of 2 people each) operating 24/7 (3 time shifts, with each team spending 8 hours underwater on the diving bell with each member having 4 hours in the bell and 4 hours out on water connected by an umbilical cable to it). As anticipated, these operations last usually for 4 weeks, forcing the personnel to live for the whole period in pressure inside the plant and its modules.

In facts the hyperbaric plant consists usually of several modules and hyperbaric chambers are based on interconnected pressurized tank containers that are able to guarantee safety and support living conditions. Indeed the different chambers are connected each other by clamps for guaranteeing the control of internal pressure. A normal hyperbaric plant, for industrial applications, includes life-support systems, submersible decompression chamber, rescue chamber, plus several auxiliary systems. The whole plant is typically containerized and installed on vessels, barges or Off-Shore Platform. Due to the risks for human life, to operate and control this plant, high professional skills are required. Indeed, these systems must be controlled by qualified operators, named Life-Support Supervisor (LSS).

Such operators are certified through their professional experiences as well as specific training programs, test and assessments; this process could be completed on real plants or on simulators.

In facts, the LSS figure is required to control directly the chamber internal pressure, and the other vital parameters for the divers like temperature, humidity and breathing gas composition.

In addition all the other parameters have to be monitored and controlled, like for example the temperature, the gas storage system through additional pressure regulators, back-up power supply and control of bell's position; it is also required to guarantee continuous communications between LSS and divers as well as other technical and operational staff (e.g. officer at ship bridge for positioning of the vessel carrying the plant; off-shore control room operators) to address the different critical issues.

3 TRAINING AND SIMULATION

In the past, the training for divers was almost based on the use of the real equipment, and just few simulators, mostly physical ones, have been developed and adopted. The majority of them is not still operational today. However there are several hyperbaric and hypobaric chambers which are used to prepare personnel to harsh ambient conditions, and some of them are used for training the divers. Examples of hyperbaric chambers are HYDRA and MEDUSA developed by HAUX, that allows to achieve 16 bar pressure (equivalent to 160 meters depth), while examples of hypobaric chambers, used for pilots is Falcon Altitude Chamber produced by ETC. Training for Life Support Supervisor (LSS) is also a necessity in space operations that have a similar complexity level of deep diving operations; for example V-HAB (Virtual Habitat) project was created to simulate the LSS of the International Space Station. In this case the simulator was based on Matlab and resulted totally virtual and able to simulate atmospheric conditions, water and food consumptions as several other factors (Czupalla 2005; Zhukov et al. 2010; Czupalla 2011).

Despite the increasing interest on computer simulation in diving operations (IMCA 2015) there are still few information about existing training solution for diving sector and, we are aware of the existence of just one commercial tool devoted to simulate an hyperbaric chamber control system (CKAS Mechatronics,

Australia) able to achieve IMCA certification (International Marine Contractors Association) for training purposes. Hence, the solution by the authors is based on modern interoperable M&S (Modeling and Simulation) and combines different models, being expected to be adopted for the development of the first simulator certified in Europe for LSS training. As mentioned above at this moment, the training of LSS is usually performed by using real chambers; therefore such operation obviously have limitations and problems; for instance, during operations on a real plant, it's almost impossible to experience and test emergency situations; at the same time, inexperienced personnel could damage the equipment, while training on the job is not possible being very dangerous for divers.

These elements as well as the necessity to supervise around the clock the deep divers in operations reduce drastically the efficiency in using real hyperbaric chambers for trainings. Due to these reasons the introduction of simulation-based training results very efficient for improving safety, reducing costs and increasing the training opportunities as it is already common in many other industrial sectors as well as in military domain. The benefits of a simulation-based training equipment devoted to test and assess LSS are evident, in facts the simulator results much more available respect to a real plant (saturated by real operations and often located overseas on the fields) and it guarantees the possibility to reproduce emergency situations. In facts existing international organizations such as IMCA (IMCA, 2015, 2016) are evaluating the advantage of simulation respect real equipment training and, in some case, they are counting one hour of training on a certified simulator double compared to an hours of work on a real plant; so training course could be shorter and cheaper; obviously the simulator costs are even lower than using real equipment.

Another benefit of simulation is the possibility to support virtual prototyping of new equipment considering not only engineering, but also operational issues. Indeed the simulation allows to replicate predefined scenarios and to repeat already performed exercises recording in an exhaustive and synchronized way the operation log for correcting wrong behaviors and systematic errors.

For these reasons the use of simulation in this field is expected to be quite preferable and it make sense to develop new solutions able to combine the plant processes and physics with the operational issues as well as with human behavioral and physiological models to deal even with this critical aspects that usually are the cause of accidents.

4 SIMULATION MODELS

The proposed architecture developed by the authors is summarized in figure 1 and includes the different main component; originally the authors have considered to support the interoperability among the different models, simulators and real equipment by adopting High Level Architecture standard.

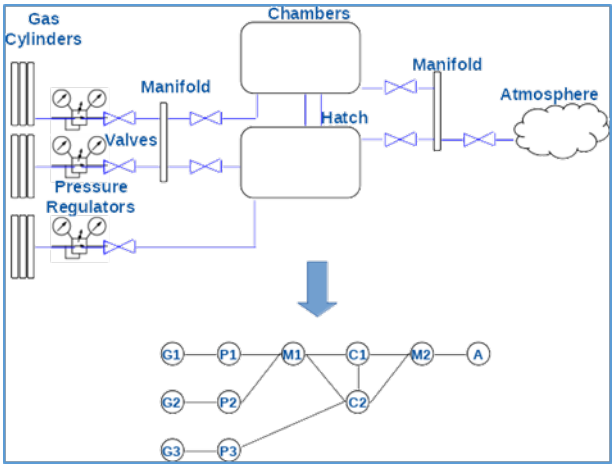

Figure 3. Gas Distribution Model

Indeed this approach is the most open and generic and could lead to significant benefits in further extensions, therefore the same architecture could be based also on different technological interoperability approaches (Kuhl et al.1999). In this case, the overall simulation turns to be based on a federation of models as proposed in figure 2, simulators and real equipment that operates as federates and are interconnected through a Run Tim Infrastructure; in this case it is possible to use meta-models to cover elements of the original systems that does not require very high detailed simulation (Kleijnen et al.2000).

This paper focuses mostly on two main aspects to be covered within the whole simulation these two models corresponds respectively to the plant processes dealing with gas physics and the human physiology and disorder modeling. The physical models of the gases have to address, for the training purposes, their dynamics and mixture considering the pressure regulators, gas cylinders, piping systems, valves, chambers, control systems, gas recuperation system as well as on-going operations and human activities. Obviously, such type of plant requires effective and redundant control system; in facts, due to safety reasons it's necessary to have more than one instrument capable to measure key parameters of the atmosphere inside, for example pressure is measured simultaneously by pressure gauges connected directly to different sections of the plant and by gas analyzers using special sensors. For these reasons, one of the need of the simulation is to cover all the equipment, devices and components present in a real plant in order to be able to be certified and to handle LSS training as it happen on real plant. Furthermore, the simulators used for training purposes need to appear pretty similar to real systems to increase immersion of the trainee during the exercises and consequently to improve the quality of learning process. As anticipated, one of the simulation key elements is the gas distribution model which reproduces all the atmospheric conditions in every part of the plant.

This model should be able to reproduce all the plant different components; in the proposed model two main objects are introduced able to couple all the plant components: Node and Arc.

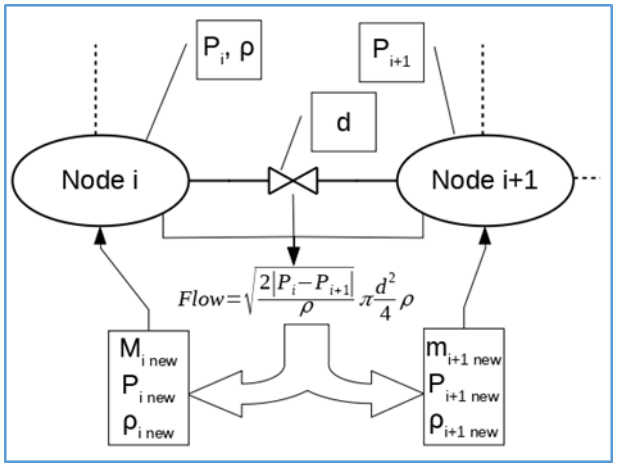

Figure 4. Calculation Process over all the Nodes

Nodes are used to model parts of the plant where parameters of gas mixture could change such as, for example, pressure regulators, manifolds, chambers and pipes' connections while Arcs are used to represent the connections among the Nodes.
This approach allows to represent the entire system as mathematical graph as proposed in figure 2.
As anticipated, the author are currently developing preliminary models to finalize the creation of new distributed simulation solutions for this context; the final goal is to create an open and interoperable environment therefore the specific characteristics of this application area require to develop tailored models and simulation engines. The development of models related to human behavior inside the hyperbaric plants represents a specific innovative components that could further improve training in this sector and it demonstrates the potential of new generation of simulators. The created physical model of the plants is based on a non-oriented graph G, composed by a N nodes and A Arc . As anticipated, each object have been modeled by means of a node, while each connection is represented by an arc.

$$G = (N,A) \quad (1)$$

For instance, i node could represent a chamber, a pressure regulator, a manifold, a gas cylinder or a long pipeline and it characterized by several variables:

$V_i(t)$ = Volume of i node at t time
$T_i(t)$ = Temperature of i node
$P_{x,i}$(t) = Partial Pressure of x gas in the $i$node
$M_{x,i}$ = Mass of x gas in the i node

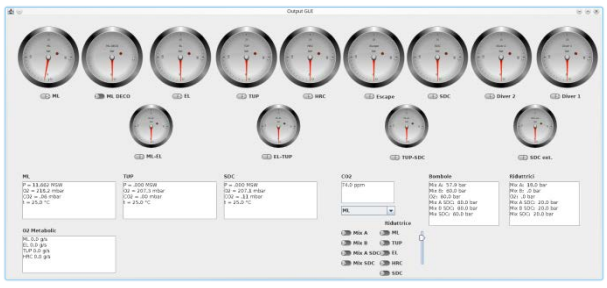

Figure 5. Control panel GUI

Each i Volume is governed by the Boyle's Law and simulated through dynamic integration of Bernoulli equation as proposed in figure 4.
With the P_i total pressure of the atmosphere mix, in the i node, resulting from the sum of the $P_{x,i}$ partial pressure of each gas component; steady state conditions could be computed based on the Dalton's law with n representing the number of moles and R the Gas Constant (8.3144598 kg m^2 s^{-2} K^{-1} mol^{-1}).

$$n_i = \sum_{x=1}^{j} n_{x,i} \quad (2)$$

$$P_i = \frac{(R \cdot n_i \cdot t_{i,})}{V_i(t)} \quad (3)$$

In facts, the Pipelines could be considered as nodes if their volume is significant, while the Arc are representing the logic connections among the different elements; in case a pipeline length and dimension is negligible it could be possible to use directly an Arc to model it as an approximation; in facts, this approach allows to simplify calculation of gas transfer in case this hypothesis is valid because only one step is required to estimate the flow between two connected Nodes.
As anticipated, the proposed model allows to optimize in terms of efficiency the calculation sequence presented in figure 4 in order to guarantee high performance even on basic hardware solutions.
This aspect from Education and Training point of view it is pretty important due to the nature of hyperbaric plant; currently some operations are proceeding pretty slowly in terms of solar time (e.g. hours). In facts often just crucial moments are tested on the field on the real equipment training in order to reduce the time for completing the assessment of the trainees as well as the instruction time. Vice versa, by simulation this limitation could be overridden especially, for education, by running a fast time simulation execution; therefore this requires to be able to reproduce the whole plant physical evolution of gases very fast.
The proposed model allows to achieve very satisfactory results even in the case of a large hyperbaric complex by continuous simulation on the Bernoulli equations for each pipeline (Arc) and module (Node), based on Runge Kutta integration technique; for the training purposes this result able to recalculate completely the plant states quickly and quite precisely.
In facts these implementation aspects have been investigated during the conceptual modeling to check the capability to achieve this objective; the authors completed an implementation in Java of the conceptual model and added also for validation and verification purposes a specific simple GUI (Graphic User Interface) based on Swing toolkit.
Obviously the final training equipment should adopt a specific interface that result graphically similar to the real ones eventually using virtual reality, physical mock up, real equipment, interactive screen, etc.

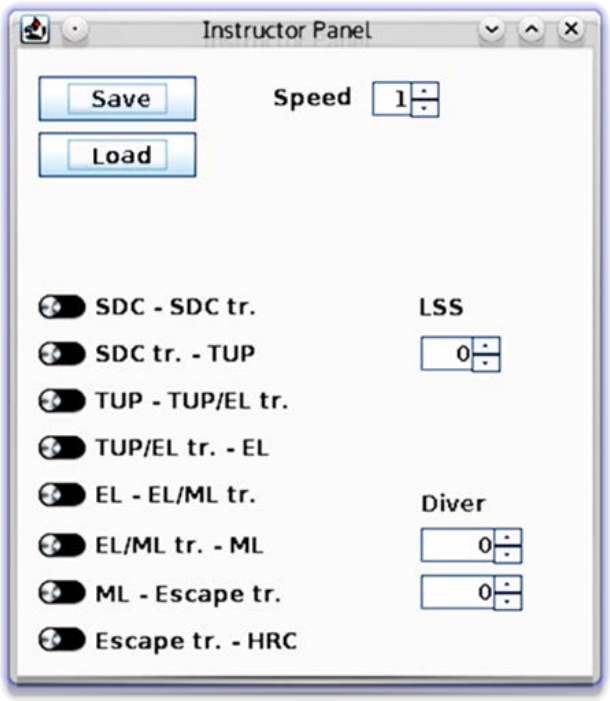

Figure 5. Instruction Panel to override Controls

Therefore also the development framework created by the authors provides an interface that reproduce in simplified way the several panels, similar to presented in the real plant for being reviewed by Subject Matter Experts (SME), such as control panel (fig. 4), and panel with valves and pressure regulators, with additional separate control panel for instructor.

In addition to these aspect, several crucial components of the hyperbaric plant need to be simulated. In facts the real control panel contains several types of elements and these devices are often characterized by different nature and/or on diverse physical principles. In some case for training it could enough just to use virtual models, therefore for other purposes or for high fidelity simulation real equipment needs to be part of the loop.

In this case, it is proposed an architecture open to support both approach; for instance the gas analyzers are digital and could make sense to use virtual models to reproduce their behavior; so it is possible to use specific federates, within the overall federation, to reproduce these elements by specific simulators or emulators. For instance, it could be integrated in the whole simulation network a single-board computer with touch screens that share objects and data with core simulation engine over a LAN (Local Area Network).

Contrary, the pressure gauges are analogous and it could be possible that is required to include the real ones into the simulation to provide the trainee with a very realistic interface able to take care of parallax, gauge oscillations and inertia affecting measure readiness. In this case it required to adopt an hardware in the loop paradigm that could be achieved by proposed architecture by creating a specific federate digital module controlling the stepper motor that moves the pointer of the gauge.

Among other subsystems of the plant, a very important one is the reproduction of communication between LSS and other personnel such as divers, technicians, officers, control room operators, etc. In this case an hard integration with simulation is not strongly necessary therefore the possibility to have a federate devoted to this aspect could provide significant benefits considering the possibility to couple voice message with events. For this purpose is suggested to use recorded messages in addition to instructor voice communications and the development of a specific module to manage this aspect. In facts due to absence of all mentioned staff during the training sessions, the only real human the LSS could interact is instructor; therefore in real plants divers are breathing special gas compositions at high pressure, which creates significant voice distortion, hence to create realistic training environment plausible voice distortion for messages arriving from 'divers' must be introduced.

5 MODELING OPERATION EFFECTS ON HUMANS WITHIN THE SIMULATION

As was mentioned, in many cases, simulation allows to significantly improve human safety, in facts to maximize its positive effect, influence of LSS's decisions on divers' health could be considered. Obviously the quantity of physiological factors which could cause effects on diver is enormous and their implementation could require a lot of resources, while most of them have very limited effect or rare impact considering that the divers are selected people with excellent health. In addition some pathologies require detailed interaction with Medical Doctors and it is not required to train the LSS on such issues. So it's necessary to choose several most important factors considering field of application of a simulator and real effects on quality of training. Based on this consideration it is useful to refer to main analyses of different phenomena and effects available in technical and scientific literature (US Navy, 2008; Evan, 2016; Fisher, 2011; Bosco).

The authors posed special attention to US Navy Diving Manual that is a reference document for the whole sector; in facts, health and safety are main issues for training of LSS and LST (Life-Support Technicians), and this manual contains a lot of information regarding underwater physiology and describes situations and symptoms of different diving disorders.

After analysis the different health care cases the following main elements were identified to be modeled for the simulation: barotraumas, hypoxia, hyperoxia, carbon dioxide poisoning, nitrogen narcosis, hypothermia, hyperthermia and various problems caused by contamination.

These disorders, which are summarized in table 1, are caused by atmosphere composition, temperature and pressure change rate, hence during simulation health indexes of every diver are calculated using data about current and previous states of the plant, for example concentration of oxygen in last 10 minutes, so the temporal evolution of state variables is very important.

Table 1. Principal Disorders included in the Simulation

Disorder and Sickness	*Cause based on Simulated parameters*	*Effects and Symptoms presented by virtual simulation*
Barotrauma	Pressure variation in time	Ear pain; Pain in front or cheekbones
Vertigo	Pressure variation in time	Vertigo Nausea
Hyperoxia	Oxygen concentration	Uncontrolled movements
CO2 poisoning	CO2 concentration	Breathing difficulties Respiratory spasms Loss of consciousness
Hypoxia	Oxygen concentration	Shortness of breath
Narcosis	Inert gas concentration (Nitrogen, Hydrogen)	Small tics and convulsive phenomena
Hypothermia	Temperature	Shivering
Hyperthermia		Sweating

From this point of view virtual humans driven by agents could be used to reproduce pathology evolution (Bruzzone et al. 2012).

In facts, it could be interesting in the proposed approach to adopt the MS2G paradigm (Modeling, interoperable Simulation and Serious Game) where a virtual environment is used to maximize the effectiveness of training by presenting through audio and/or video effects the impact of the disorders on the people (Bruzzone et al.2014). From this point of view, it should be outlined that in some cases it's difficult to provide enough data to decide if certain medical condition should be applied; for instance, hypoxia could be caused by stratification of atmosphere inside the chamber in case of low gas circulation rate. Another example is contamination which could be caused by different agents placed inside the chamber, usually transported from out of the plant after the completion of an underwater work shift. For these reasons, it could be more effective to generate, some of these disorders, manually by direct commands from the instructor's control panel. For instance, he could inject within a simulated virtual diver the symptoms of hypoxia to check trainee reaction. However, it's important to distinguish events generated automatically from these introduced by the instructor; from this point of view is useful to block inconsistent situation, for example, to avoid that a simulated diver presents barotrauma symptoms while there is no any pressure change in that zone. Currently the training courses are performed mostly by using real hyperbaric chambers without leaving personnel inside; in these case the trainee could understand if system's parameters and pressure dynamics respect safety limits only by instructor feedback or by comparison of the instrument measures respect table values. For instance the maximum compression rate depends on depth (pressure inside) and could be compared with expected trends on tables. Furthermore, the traditional approach does not exclude human error and misses completely some aspects of life support, such as the control of carbon dioxide concentration, so it cannot guarantee that training is really performed correctly; obviously these aspects are compensated by the experience and skill of the instructors that pose questions to the trainees to verify their preparation and understanding. Therefore, these considerations make it evident the big potential of new simulations able to consider human behavior and physiological modeling to improve safety in this field.

CONCLUSIONS

The model developed by the authors as well as its preliminary implementation allows to simulate the training environment for LSS as it is experienced from the real control panel of hyperbaric chambers.

The simulation is open to include all the functionalities required for supporting the instructor in injecting and controlling the exercises. In facts, the resulting simulator is scalable and it allows to reconfigure the hyperbaric plant in an easy way in case of the necessity to adapt it to specific installations or training courses. At the same time the architecture is open to integrated further models in order to extend the training equipment functionalities and/or the scope of this virtual framework. Currently, further investigations are ongoing for finalizing all models definition of a case study related to an existing hyperbaric plant that will be used to finalize the Verification, Validation and Accreditation (VV&A).

REFERENCES

Amico Vince, Bruzzone A.G., Guha R. (2000) "Critical Issues in Simulation", Proceedings of Summer Computer Simulation Conference, Vancouver, July

Bruzzone A. G., F. Longo, M. Agresta , R. Di Matteo, & G. L.Maglione (2016) “Autonomous systems for operations in critical environments”, Proc. of the M&S of Complexity in Intelligent, Adaptive and Autonomous Systems and Space Simulation for Planetary Space Exploration, Pasadena, CA, USA, April

Bruzzone, A. G., Massei, M., Tremori, A., Longo, F., Nicoletti, L., Poggi, S., Bartolucci C., Picco E. & Poggio, G. (2014) “MS2G: simulation as a service for data mining and crowd sourcing in vulnerability Reduction”. Proc. of WAMS, Istanbul, September

Bruzzone, A. G., Frascio, M., Longo, F., Massei, M., Siri, A., & Tremori, A. (2012) "MARIA: An agent driven simulation for a web based serious game devoted to renew education processes in health care", Proceedings of the International Workshop on Innovative Simulation for Health Care, Vienna, Austria, pp. 188-195

Bruzzone A.G., Cerruto M., Cotta G. (1997) "VAED: Virtual Aided Engineering Design", Tech.Report of ICAMES, ENSO, Bogazici University, Istanbul, May 10-16

Bruzzone A.G., Mosca R., Pozzi Cotto S., Simeoni S. (2000) "Advanced Systems for Supporting Process Plant Service", Proceedings of ESS2000, Hamburg, Germany, October

Czupalla, M., Horneck, G. and Blome, H.J. “The conceptual design of a hybrid life support system based on the evaluation and comparisons of terrestrial testbeds”, Adv. Space Res. Vol. 35, pp. 1609-1620, 2005

Czupalla, Markus The Virtual Habitat – Integral Modeling and Dynamic Simulation of Life Support Systems., Ph.D. Thesis Technische Universität München, Verlag Dr. Hut 2011

Department of the Navy (2005) “US Navy Diving Manual”, US Navy Department, Washington, DC, August 15

Evan J. (2005) “The Professional Diver's Handbook|, Submex

Fisher D. L., Rizzo M., Caird J., & Lee J. D. (2011) “Handbook of driving simulation for engineering, medicine, and psychology”, CRC Press.

Graczyk, T., Matejski, M., & Skorski, W. (1970) “Methodology Of Underwater Monitoring”, WIT Transactions on the Built Environment, 27

IMCA (2015) “Guidance on the Use of Simulators”, IMCA C 014 Rev. 4 March 2015

IMCA (2016) “Guidance for the safe and efficient operation of remotely operated vehicles”, IMCA R 004, Rev. 4

Kleijnen, J. P., & Sargent, R. G. (2000) “A methodology for fitting and validating metamodels in simulation”, European Journal of Operational Research, 120(1), 14-29

Kuhl, F., Weatherly, R., & Dahmann, J. (1999) “Creating computer simulation systems: an introduction to the high level architecture” Prentice Hall PTR.

Martin, A. Y. (2013) “Unmanned maritime vehicles: Technology evolution and implications”, Marine Technology Society Journal, 47(5), 72-83

Naquet, R., & Rostain, J. C. (1988) “Deep-diving humans”, Physiology, 3(2), 72-75

Rebikoff, D. (1954) “Underwater color cinematography”, Journal of the Society of Motion Picture and Television Engineers, 63(2), 55-60

US Navy, (2008) “US Navy Diving Manual”, Dept.of the Navy Report Rev 6, Washington DC

Zhukov, A., Czupalla, M. and Stuffler, T. (2010) “Correlation of the ISS Life Support System Simulation with ANITA data”, SAE Technical Paper. 2010-01-0205

A MULTIDISCIPLINARY SIMULATION TOOL FOR HEALTHCARE EMERGENCY MANAGEMENT

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ABSTRACT
The aim of this research is to propose a multidisciplinary and integrated solution for healthcare system analysis. The specific goal of the simulation model is the development of an analytical algorithm to support healthcare rescuers to define how to make optimal choices in the face of risk (or uncertainty). The methodological approach integrates three aspects: 1) triage algorithm, to assess patients' condition 2) multi-criteria analysis, to define a ranking of hospitals and 3) emergency simulation. Medical staff, through the mathematical application of the triage algorithm, assesses patients' condition by assigning them a severity code. Then, through a multi-criteria approach a ranking of hospitals is defined. Thus, the decision maker can easily find the most suitable hospital where transfer patient. Finally, the model is simulated through Flexsim Software©. The research tries to overcome the qualitative evaluation that characterize the traditional healthcare models. The model is implemented in a real case study concerning an emergency scenario in a petrochemical plant.

Keywords: Emergency management, Emergency simulation, triage, decision making

1. INTRODUCTION

In recent years the focus about operators' health and safety is growing. With technological innovation, industrial plants have become increasingly complex and the accident management inside them is always more difficult. The literature analysis shows that publications on issues of emergency management during an industrial disaster are growing (De Felice *et al.*, 201 a). Emergency management is a very complex process, which involve many different actors (Bruzzone *et al.*, 2015). One of the main aspects of emergency management is the healthcare process (Christian *et al.*, 2006). During a disaster it is necessary to develop a healthcare plan to protect operators' safety. Healthcare process during an emergency is based on two fundamental aspects: 1) patients' severity evaluation and 2) choice of hospital where patients have to be cured. These two activities require the human decisions. Unfortunately, during emergencies, the human reliability decreases, because it increases the human error probability (De Felice *et al.*, 2016 b). It is necessary to develop an analytical and objective model to help the decision maker during emergency conditions and to reduce human errors. Literature review highlights that the most healthcare emergency models are strongly related to subjective decisions of operator (Considine *et al.*, 2007). The goal of the present research is to develop a healthcare integrated model to manage emergency conditions. The research integrates different traditional systems to develop an analytical – mathematical model for healthcare emergency management. In detail, the paper presents a new emergency triage model, which allows to identify and assess patients' conditions in a few minutes, using a mathematical algorithm. In addition the research proposes a multi-criteria approach, based on Analytic Hierarchy Process (AHP), developed by Saaty (1977), to define a ranking of hospitals in which to lead patients. The proposed model is implemented in a real case study to test healthcare management during an emergency condition. Finally, it is worthy to note that the model is simulated through Flexsim 2017 software. Outcomes drive the actions of medical staff to provide the best care for a patient. The present research overcomes literature limitations about the traditional models of healthcare management, defining a new mathematical tool for emergency healthcare analysis and simulation. The rest of the paper is organized as follows. Section 2 presents a literature review on triage emergency model. Section 3 describes the proposed methodological approach. Section 4 describes the emergency scenario under study. Finally, in section 5, conclusions are analyzed.

2. LITERATURE REVIEW

Literature on triage models is very rich, because aspects of human healthcare have a key role during an emergency management. Following, some of best known triage models are presented. Canadian triage and acuity scale (CTAS) is a triage model developed in the 1990 in Canada (Warren *et al*., 2008). CTAS uses a list of clinical symptoms to assess the triage level (Murray, 2003). It defines a scale with five levels:

- Resuscitation: patient has a heart attack and he risks his life;
- Emergent: patient is seriously injured;
- Urgent: patient's condition may worsen;
- Less urgent: patient has no serious injuries;
- Non urgent: patient's condition is not pejorative.

Australasian triage scale (ATS) is a triage model developed in the 1994 in Australia. All patients should be assessed by a doctor who analyzes patient's conditions (Considine *et al.*, 2004). ATS model provides five levels of severity (Table 1).

Table 1: ATS levels

ATS Triage Scale	
Category	Category description
1	Immediately life-threatening
2	Imminently life-threatening
3	Potentially life-threatening
4	Potentially serious or urgency situation
5	Less urgent

Manchester triage system (MTS) was developed in Great Britain. It has a five level scale (Roukema et al., 2006). MTS uses 52 diagrams which represent patient's symptoms. Diagrams allow to evaluate patient's conditions. When a patient shows symptoms, the doctor examines his situation and he determines the treatment priority according to the triage scale (Grouse et al., 2009). Emergency severity index (ESI) is a triage algorithm developed in the USA in the late 1990 (Eitel *et al*., 2003). Triage levels depend on the patient's severity and necessary resources. ESI model is based on four points decision. They reduced to four key questions:

1. Does this patient require immediate life-saving intervention?
2. Is this a patient who shouldn't wait?
3. How many resources will this patient need?
4. What are the patient's vital signs?

The answer to these questions defines five levels of triage model assessment (Platts Mills *et al*., 2010).
Simple triage and rapid treatment (START) system is a triage model developed in 1980 in California (Benson *et al.*, 1986). It allows to quickly assess the victims in 15 seconds. After the first evaluation, wounded are visited depth. The model defines four different triage levels (Kahn *et al*., 2009) (Table 2).

Table 2: START triage scale

START Triage Scale	
Category	Description
	Decesead
	Providing immediate care
	Provide treatment within few hours
	Low gravity

There are national triage models, but also models developed by international organizations such as NATO. Table 3 shows NATO guidelines triage scale (McGrath *et al*., 2003).

Table 3: NATO triage scale

NATO triage scale	
Category	Description
	Imminent death
	Serious injury
	Potentially serious injury
	Minor injury

Traditional triage models are very qualitative and they do not use mathematical models and numerical algorithms (Robertson, 2006). Patient's analysis is determined by subjective assessment of medical experts. In the literature, there are several mathematical models related to health emergency management. Most of these models are related to patient flow analysis in emergency departments. But literature is lacking in mathematical models of triage evaluation. Coats and Michalis (2001), propose a mathematical modeling of patient flow trough an accident and emergency department. The model constructed was not an accurate representation of patient flow because of the large number of assumptions that had to be made in the preliminary model. De Bruin *et al*. (2007) investigate the bottlenecks in the emergency care chain of cardiac in-patient flow. The primary goal is to determine the optimal bed allocation over the care chain given a maximum number of refused admissions. Another objective is to provide deeper insight in the relation between natural variation in arrivals and length of stay and occupancy rates. Costa *et al*. (2003), propose a mathematical modelling and simulation for planning critical care capacity. The combination of appropriately analysing raw data and detailed mathematical modelling provides a much better method for estimating numbers of required beds.

The developed model allows to define an iterative triage algorithm to assess patient's condition. Also, through a score model it can identify the optimal hospital where cure the patient. AHP has been used in several healthcare studies (Liberatore *et al.*, 2008). For example, Dolan et al., (1993) used AHP to verify the conditions of use of endoscopy. A group of experts formed by 25 patients and 20 doctors, analyzed a five-criteria: cause of bleeding, test complication, cost, length of stay and bleeding. Castro *et al.*, (1996) used AHP to analyze upper abdominal pain. The considered criteria were: cost, discomfort, risk and diagnostic ability. Saaty and Vargas (1998) defined an AHP model to show how can incorporate expert judgment for medical diagnosis. Bahill et al., (1995) used AHP model to define a decision support system to help speech clinicians diagnose children who have begun to stutter.

3. METHODOLOGICAL APPROACH

The proposed healthcare model defines a numerical indicator to assess patient's condition and the best hospital where conduct them. The methodological approach is divided into three different steps as depicted in Figure 1:

- Phase#1: Hybrid triage algorithm for the evaluation of patients;
- Phase#2: Evaluation of hospitals near the accident site, to establish a hospital ranking;
- Phase#3: Emergency simulation.

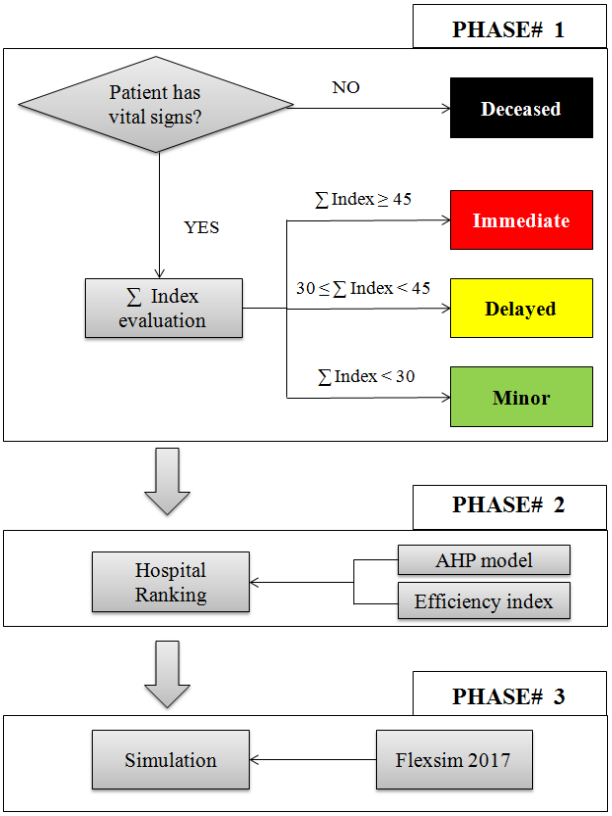

Figure 1: Methodological approach flowchart

In the following sections a description of each phase is provided.

3.1. Phase# 1: Triage hybrid algorithm

Triage hybrid model identifies four levels of emergency. The basic structure of the model is acquired by the START model and the ESI model. But in contrast with these traditional models, triage algorithm combines numerical coefficient to define the patient's level of severity.
Patient's assessment is developed by the health team. Table 4 summarizes triage scale of hybrid algorithm. It describes:

- Level;
- Name
- Time;
- Symptoms.

Table 4: Hybrid triage algorithm scale

Hybrid triage scale			
Level	Name	t (min)	Condition
	Decesead	-	Not survive
	Immediate	10	Very serious
	Delayed	45	Medium serious
	Minor	120	Less serious

For the evaluation of patients the new model involves the use of a quantitative table (Table 5). For each symptom is defined a weight (weights are obtained from the literature analysis). In addition, medical staff visiting the patient defines a value of severity for each symptom. It calculates the index of each symptom with the following formula:

$$Index = Severity \times Weight \quad (1)$$

Finally the sum of indices defines a total index, which represents the patient's condition.

$$21 \leq \sum index \leq 63 \quad (2)$$

If a vital function (heart beat, breathing, injury) is absent, patient is evaluated "deceased"
else if:

$$\sum index \geq 45 \quad (3)$$

patient is evaluated "immediate";
else if:

$$30 \leq \sum index < 45 \quad (4)$$

patient is evaluated "delayed";
else if:

$$\sum index < 30 \quad (5)$$

patient is evaluated “minor”.

Table 5: Index triage

Index Triage								
Factors	Severity				Weight			Index
	1	2	3	Absent	0.5	1.5	5	
Level of consciousness						x		
Heart beat							x	
Breathing							x	
Mobility					x			
Panic					x			
Injury							x	
Circulation						x		
Ventilation						x		
Age					x			
								TOT

3.2. Phase# 2: Ranking of hospitals

The model allows to evaluate hospitals to establish an evaluation ranking. The model evaluates hospital conditions trough different criteria. For each criterion, weights and evaluation are defined (Figure 2).

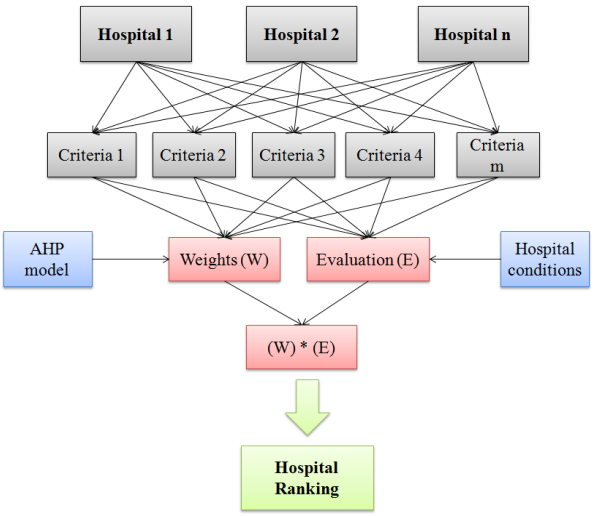

Figure 2: Rating hospitals flowchart

Weights of criteria are identified through AHP. Traditional AHP model is developed through tree level hierarchy. The top level is the main goal of a decision problem, the lower level is the criteria and finally there are alternatives.

In this case, the model only provides for two levels: goal and criteria, which allow to define a criteria ranking. The model is divided into three steps:

- Hierarchy construction;
- Pairwise comparison and relative weight estimation;
- Priority weight vector calculation.

The AHP model defines weights of criteria. After weights ranking, it is possible to assess the evaluation of hospitals (Table 6). The evaluation depends on the hospital conditions. If hospital conditions are good, then the valuation values are high, otherwise they are low.

Table 6: Hospital ranking

Hospital ranking				
Hospital Criteria	Weight criteria (W)	Evaluation (E)		
		Hospital 1	Hospital 2	Hospital n
1	0.30			
2	0.27			
3	0.24			
m	0.19			

For each hospital is calculated the efficiency index (Eindex):

$$Eindex = Weight \; x \; Evaluation \quad (6)$$

and finally, for each hospital is calculated the overall efficiency index (TOTEindex):

$$TOTEindex = \sum Eindex(criterion) \quad (7)$$

Hospitals are classified considering the total efficiency index.

3.3. Phase# 3: Simulation

The last step of the model represents the simulation of a healthcare emergency condition in a software environment. Simulation is one of the most used tools for process optimization, because it allows to represent real systems with computer. The importance of simulation is growing in recent years, since it is one of the fundamental pillars of the industry 4.0 revolution. The simulator used in the research is “Flexsim 2017”. It allows to observe the various steps of the emergency management and to analyze interactive dashboard for the evaluation of healthcare performance. Flexsim was chosen because it is a dynamic simulation system that allows to manage deterministic variables, but also probabilistic values, represented through probability distributions. In particular, the speed of ambulances may vary according to traffic conditions, and also the patient's evaluation time may be variable. A probability distribution is used to define these factors in the simulative environment. Figure 3 shows the working simulation software environment.

The simulator was born to model industrial system, but through various customizations it was possible to use it to healthcare simulations.

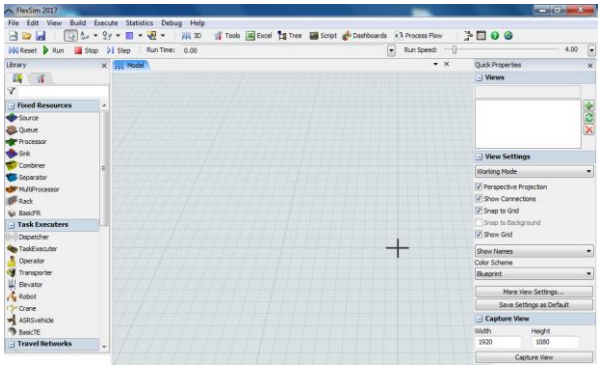

Figure 3: Flexsim working environment

4. EXPERIMENTAL DESIGN: A CASE STUDY

The proposed case study provides a description of an emergency situation in a petrochemical industry. The incident event is the loss of hydrogen sulphide from a tank for the refining used oils. The cause of the accident is a failure of the pumping system that has caused a leak in the fuel tanks. Maintenance workers did not notice the problem that was degenerated causing an emergency condition. After, the alarm is triggered, all employees leave the plant using the emergency exit, and they go to the safe point. The safety manager notes that there are three wounded. The internal emergency team gives them the first care, meanwhile the safety manager calls external healthcare to assess the possible hospitalization. The aim of the model is to evaluate the condition of the injured and to choose the best hospital in which hospitalize them. The case study simulates an emergency management in a dynamic simulation environment using a probabilistic approach to define different variables.

4.1. Phase# 1: Triage hybrid algorithm

Three workers were injured during the incident. Neither of them has absent vital signs, then for all operators is necessary to evaluate triage index. Table 7 shows a triage index chart for operator 1.

Table 7: Triage index (Operator 1)

Triage index (Operator 1)								
Factors	Severity				Weight			Index
	1	2	3	Absent	0.5	1.5	5	
Level of consciousness		x				x		3
Heart beat		x					x	10
Breathing			x				x	15
Mobility	x				x			0.5
Panic	x				x			0.5
Injury		x					x	10
Circulation			x			x		4.5
Ventilation	x					x		1.5
Age	x				x			0.5
								45.5

The assessment injured' condition is performed only by authorized medical personnel. The same analysis is repeated for all the operators with the following results:

- Triage index (operator 1) = 45.5
- Triage index (operator 2) = 47
- Triage index (operator 3) = 35

Table 8 shows the triage assessment for three operators.

Table 8: Triage assessment

Triage assessment			
Operator	Level	Triage index	t (min)
1	Immediate	45.5	10
2	Immediate	47	10
3	Delayed	35	45

4.2. Phase# 2: Rating hospitals

The case study identifies four hospitals near the accident site. The considered criteria are:

- Hospital departments;
- Distance from accident site;
- Number of roads between hospital and accident site;
- Beds vacancies;
- Number of ambulances.

A group of four experts on health and logistic defines criteria preferences using Saaty semantic scale. Figure 4 shows an example of pairwise comparison matrix in a "Superdecision" software. The judgments of experts are significant because CI = 0.03 ≤ 0.1. Superdecisions software returns a ranking between different criteria which are used as weights for the next score analysis. beds = 13% , departments = 35%, distance = 32%, road = 13% and transport = 7%. It is necessary to know the conditions of individual hospitals (Table 9) to identify evaluation index (E) for each criterion and hospital.

Table 9: Hospital conditions

Hospital conditions				
Criteria	Hospital 1	Hospital 2	Hospital 3	Hospital 4
Number of departments	6	5	5	5
Distance (km)	3.4	5.5	6	4.5
Roads	3	4	5	5
Beds	370	165	221	234
Transport	2	1	2	3

The evaluation index is a number between 0 and 100 and it is evaluated by considering the information on individual hospitals.

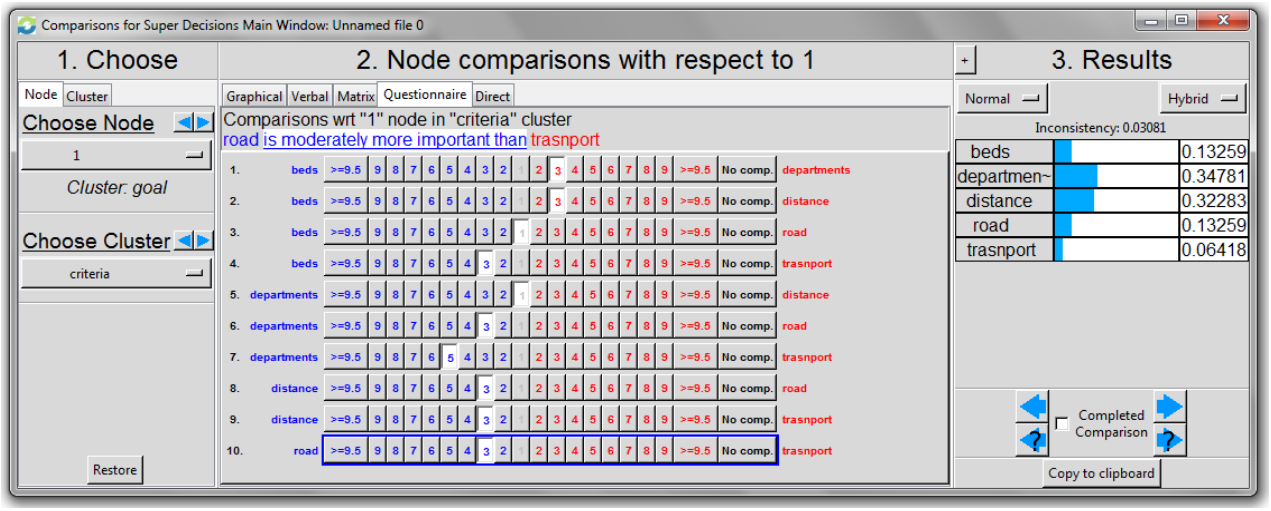

Figure 4: Pairwise comparison – superdecisions software

The evaluation values of table 10 have been developed considering descriptive factors listed in Table 9. For example, considering the number of departments, hospital 1 is the most equipped. So the presented methodology assigns to hospital 1 a value of 90. Other hospitals have all 5 departments, so the methodology associates an evaluation value of 72, slightly lower than hospital 1. Table 10 shows weight and evaluation for each criterion and each hospital. Finally, Table 11 shows efficiency index (WxE) and total efficiency index for each hospital. It shows a hospital ranking. Hospital 1 has achieved the highest score and it is the preferred, followed from hospital 4.

Table 10: Weights (W) and Evaluation (E)

Weights and evaluation					
Criteria	Weight (W)	Evaluation (E)			
		H1	H2	H3	H4
Departments	35	90	72	72	72
Distance (km)	32	90	80	75	85
Roads	13	45	68	90	90
Beds	13	90	40	54	57
Transport	7	90	30	60	90

Table 11: Efficiency index

Efficiency index				
Criteria	W x E			
	H 1	H2	H3	H4
Departments	3150	2520	2520	2520
Distance (km)	2880	2560	2400	2720
Secondary road	585	884	1170	1170
Beds	1170	520	702	741
Transport	630	210	420	630
	8415	6694	7212	7781

4.3. Phase# 3: Simulation

The case study hypothesized an accident in a petrochemical company, that involved different operators. 3 workers are injured and they have been classified using a hybrid triage algorithm (Table 8). A hospital ranking has been defined in Table 11. All wounded should be transported to the hospital 1, because it has the best score. But according data on Table 9, hospital 1 has only two ambulances. So the two "red" wounded are admitted to hospital 1, while "yellow" injured is admitted to hospital 4, which is the second preferred hospital (Table 12). The case study was simulated with "Flexsim 2017" (Figure 5).

Table 12: Strategic emergency plan

Strategic emergency plan		
Operator	Level	Recovery
1	Immediate	Hospital 1
2	Immediate	Hospital 1
3	Delayed	Hospital 4

The simulation shows that 2 ambulances depart from hospital 1 and they will transport "red"operators and 1 ambulance departs from hospital 4 and it will transport "yellow" operator. For model construction it was necessary to reconfigure industrial objects in healthcare objects. For example, the internal industrial handling system is converted into ambulances. Simulation allows to manage the triage process, identifying each patient with a shirt of a different colour related to his triage level. Also simulation manages the logistic process by analyzing the total time necessary for emergency management. Simulation assumptions are:

- ambulance speed: triangular distribution (50, 70, 80,0) km/h. Probability distribution allows to evaluate the different traffic conditions and therefore the different speeds of the ambulance;

- patient load time: triangular distribution (3,5,7,0) min. Probability distribution allows to evaluate the different assessment conditions.

Italian Red Cross defines costs of emergency management. For each ambulance fixed costs are 30 € / journey while variable costs are 0.91 € / minute.

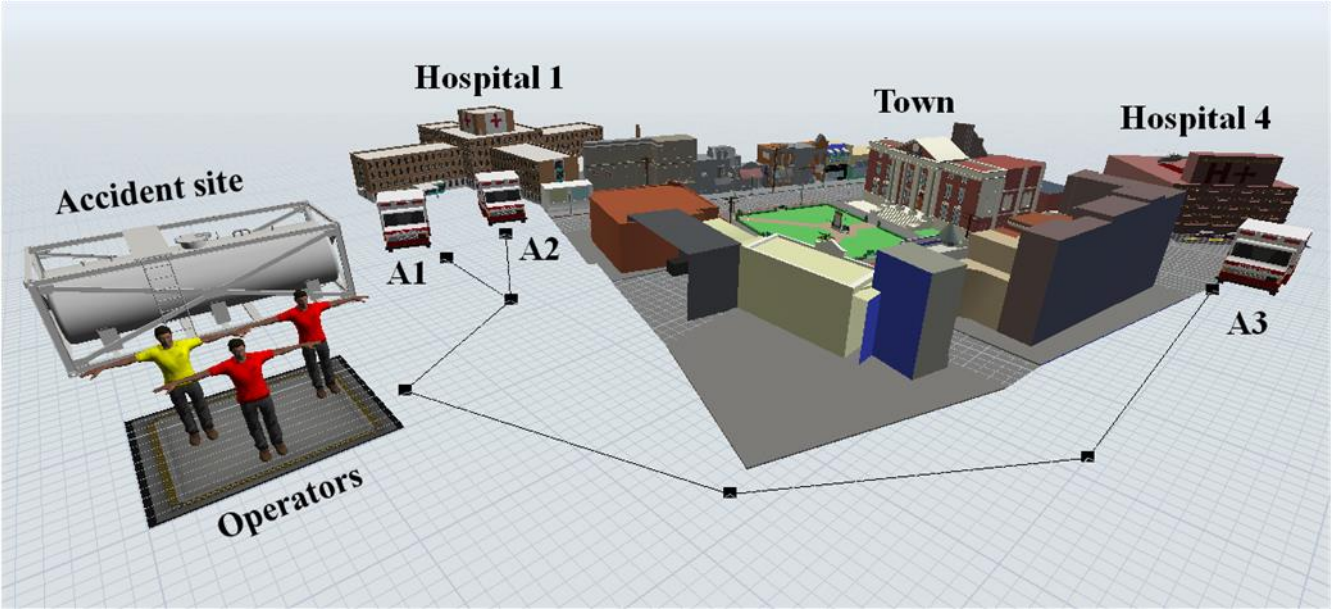

Figure 5: Simulation

These parameters are included in the simulation. Figure 6 shows a typical dashboard of KPIs obtained by Flexsim simulation.

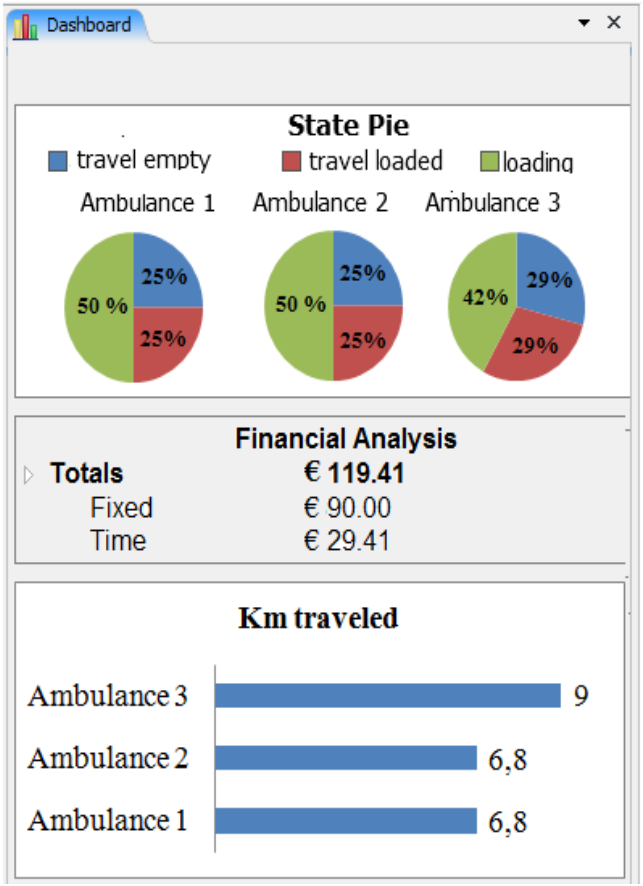

Figure 6: Simulation dashboard

In the first simulation all injured were hospitalized within 13 minutes. The dashboard shows the number of kilometers travelled by 3 ambulances and the percentages of time divided by empty travel, load travel and patients loading time. The highest percentage of time is relative to the patient load. Finally, the simulation also assessed the economic aspect of emergency management. In the first analysis the total cost of healthcare emergency management was 119.41 €. The analysis does not consider the hospital costs.
Ambulance speeds and patient evaluation/loading times are variable, because they are represented by probability distributions. For this reason, 25 simulations were performed to identify the output values variability related to: total emergency management costs (Figure 7) and emergency completion time (Figure 8). The average total cost of emergency management is 120.37 minutes, while the standard deviation is 1.69 minutes. The average time of emergency management is 13.70 minutes, while the standard deviation is 0.74 minutes.

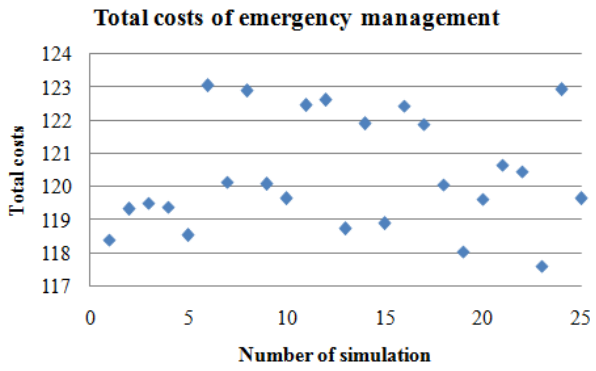

Figure 7:Distribution of costs resultant of 25 simulation

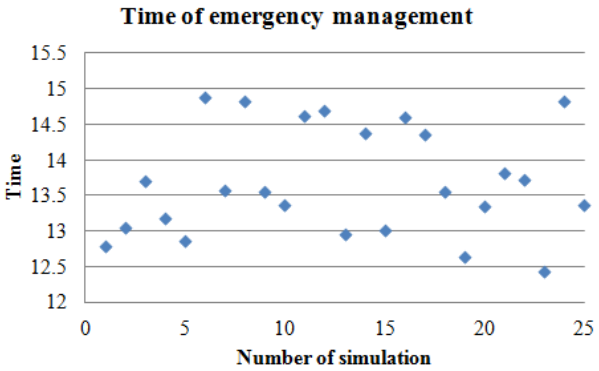

Figure 8: Distribution of time resultant of 25 simulation

5. CONCLUSION

Safety is the most important element in the business management. In particular, during the emergency condition, people are subject to high risks. It is necessary to manage healthcare process, to avoid tragic and deadly consequences. Unfortunately, during emergency situations, the decision maker is subject to a lot of stress, so it could make bad choices. It is necessary to develop a decision support system that helps decision-maker in the healthcare process during an emergency condition. Traditional healthcare models are subjective and do not work with mathematical algorithms. Traditional health management models, that use mathematical approaches, analyze only patient flows, while there are not many TRIAGE mathematical models for patient evaluation in the literature.
The research has developed an analytical-mathematical model which has two objectives:

- develop a hybrid triage algorithm for patient evaluation;
- define a multicriteria mathematical tool to identify a ranking between the nearest hospitals to the accident site.

The two models return numeric values and help the decision maker to make the right decision. The model has been implemented in a real scenario: an accident in petrochemical company in which three workers had been injured. Finally the accident was simulated in a virtual environment with the help of Flexsim 2017 software to identify key performance indicators to manage the healthcare emergency process. The simulation model introduces stochastic variables, so 25 simulations were performed to analyze the variability of two outputs: the emergency management time and the total cost of emergency management.The dashboard obtained with simulation is critical because it allows to evaluate improvements in the healthcare management process through simulation tools. The emergency simulation allows to identify the criticality of the process and make the necessary optimizations.
An interesting future research development is the analysis of the performance variability of emergency processes through new representation models such as the "*functional resonance analysis method*" (FRAM). The goal is to evaluate how a wrong upstream choice can negatively/positively affect other downstream choices.

REFERENCES

Bahill A.T., Bharathan K., Curlee R., 1995. How the testing techniques for a decision support system changed over nine years. IEEE Transaction on System, Man and Cybernetics, 25(12), 1533-1542.

Benson M., Koenig K.L., Schultz C.H., 1996. Disaster triage: START, then SAVE—a new method of dynamic triage for victims of a catastrophic earthquake. Prehospital and disaster medicine, 11(02), 117-124.

Bruzzone, A.G., Cirillo, L., Longo, F., Nicoletti, L., 2015. Multi-disciplinary approach to disasters management in industrial plants. Simulation Series 47(10), pp. 139-147.

Castro F., Caccamo L.P., Carter K.J., Erickson B.A., Johnson W., Kessler E., Ruiz C.A., 1996. Sequential test selection in the analysis of abdominal pain. Medical Decision Making, 16(2), 178-183.

Christian M.D., Hawryluck L., Wax R.S., Cook T., Lazar N.M., Herridge M.S., Burkle F.M., 2006. Development of a triage protocol for critical care during an influenza pandemic. Canadian Medical Association Journal, 175(11), 1377-1381.

Coats, T. J., & Michalis, S. (2001). Mathematical modelling of patient flow through an accident and emergency department. Emergency Medicine Journal, 18(3), 190-192.

Considine J., Botti M., Thomas S., 2007. Do Knowledge and Experience Have Specific Roles in Triage Decision-making? Academic emergency medicine, 14(8), 722-726.

Considine J., LeVasseur S.A., Villanueva E. 2004., The Australasian Triage Scale: examining emergency department nurses' performance using computer and paper scenarios. Annals of emergency medicine, 44(5), 516-523.

Costa, A. X., Ridley, S. A., Shahani, A. K., Harper, P. R., De Senna, V., & Nielsen, M. S. (2003). Mathematical modelling and simulation for planning critical care capacity. Anaesthesia, 58(4), 320-327.

De Bruin, A. M., Van Rossum, A. C., Visser, M. C., & Koole, G. M. (2007). Modeling the emergency cardiac in-patient flow: an application of queuing theory. Health Care Management Science, 10(2), 125-137.

De Felice, F., Falcone, D., Petrillo, A., Bruzzone, A., Longo, F., 2016. A simulation model of human decision making in emergency conditions. 28th European Modeling and Simulation Symposium, EMSS 2016, Larnaca; Cyprus; 26 September - 28 September 2016 pp. 148-154.

De Felice F., Petrillo A., Zomparelli F., 2016. A Hybrid Model for Human Error Probability Analysis. IFAC-PapersOnLine, 49(12), 1673-1678.

Dolan J.G., Bordley D.R., Miller H., 1993. Diagnostic strategies in the management of acute upper gastrointestinal bleeding: Patient and physician preferences. Journal Gen Intern Med 8(10), 525-529.

Eitel D.R., Travers D.A., Rosenau A.M., Gilboy N., Wuerz R.C., 2003. The emergency severity index triage algorithm version 2 is reliable and valid. Academic Emergency Medicine, 10(10), 1070-1080.

Grouse A.I., Bishop R.O., Bannon A.M., 2009. The Manchester Triage System provides good reliability in an Australian emergency department. Emergency Medicine Journal, 26(7), 484-486.

Kahn C.A., Schultz C.H., Miller K.T., Anderson C.L., 2009. Does START triage work? An outcomes assessment after a disaster. Annals of emergency medicine, 54(3), 424-430.

Liberatore M.J., Nydick R.L., 2008. The analytic hierarchy process in medical and health care decision making: A literature review. European Journal of Operational Research, 189(1), 194-207.

McGrath S., Grigg E., Wendelken S., Blike G., De Rosa M., Fiske A., Gray, R., 2003. Artemis: A vision for remote triage and emergency management information integration. Dartmouth University, 9.

Murray M., 2003. The Canadian Triage and Acuity Scale: A Canadian perspective on emergency department triage. Emergency Medicine Australasia, 15(1), 6-10.

Platts Mills T.F., Travers D., Biese K., McCall B., Kizer S., LaMantia M., Cairns C.B., 2010. Accuracy of the Emergency Severity Index triage instrument for identifying elder emergency department patients receiving an immediate life - saving intervention. Academic Emergency Medicine, 17(3), 238-243.

Robertson S., 2006. Evolution of triage systems. Emerg Med Journal, 23(2): 154–155.

Roukema J., Steyerberg E.W., Van Meurs A., Ruige M., Van der Lei J., Moll H.A., 2006. Validity of the Manchester Triage System in paediatric emergency care. Emergency medicine journal, 23(12), 906-910.

Saaty T.L., 1977. A scaling method for priorities in hierarchical structures. Journal Math. Psycol., 15(3), 234-281.

Saaty T.L., Vargas, L.G., 1998. Diagnosis with dependent symptoms: Bayes theorem and the analytic hierarchy process. Operations Research, 46(4), 491-502.

Warren D.W., Jarvis A., LeBlanc L., Gravel J., 2008. Revisions to the Canadian triage and acuity scale paediatric guidelines (PaedCTAS). Canadian Journal of Emergency Medicine, 10(3), 224-233.

ACKNOWLEDGMENTS

This research represents a result of research activity carried out with the financial support of University of Naples Parthenope, namely "Bando di sostengo alla ricerca individuale per il triennio 2015-2017. Annualità 2016".

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