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HYBRID CONCEPTUAL MODELING FOR SIMULATION: AN ONTOLOGY APPROACH DURING COVID-19

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ABSTRACT

The recent outbreak of Covid-19 caused by SARS-CoV-2 infection that started in Wuhan, China, has quickly spread worldwide. Due to the aggressive number of cases, the entire healthcare system has to respond and make decisions promptly to ensure it does not fail. Researchers have investigated the integration between ontology, algorithms and process modeling to facilitate simulation modeling in emergency departments and have produced a Minimal-Viable Simulation Ontology (MVSimO). However, the “minimalism” of the ontology has yet to be explored to cover pandemic settings. Responding to this, modelers must redesign services that are Covid-19 safe and better reflect changing realities. This study proposes a novel method that conceptualizes processes within the domain from a Discrete-Event Simulation (DES) perspective and utilizes prediction data from an Agent-Based Simulation (ABS) model to improve the accuracy of existing models. This hybrid approach can be helpful to support local decision making around resources allocation.

1 INTRODUCTION

The idea of merging different methodologies for a hybrid model to create accurate forecasting of healthcare demand has gotten a lot of attention. Combining approaches has a great practical appeal for simulation modelers in complex and heterogeneous domains like emergency departments or better known as admission and emergency (A&E) departments in the United Kingdom. This approach is practical especially in complex domains because most real-world issues and systems have many diverse aspects and characteristics, and there is rarely a single method that is perfectly suited to capture all of them. (C.Brailsford et al. 2019). With the rapidly spreading of Covid-19, it is necessary to have a quick modeling solution with a more reasonable healthcare resource planning and allocation. But, it is challenging to perform hybridization methods compared to the single-approach methods, because it requires experts who are skilled in several ways (Lather and Eldabi 2020).

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To address this issue, we propose creating an Ontology-based Conceptual Model for Simulation in Healthcare (OCMS-H), which serves as a framework for simulation modeling to reflect the impact of Covid-19 in emergency departments. OCMS-H profits from the abundance of data available in the industry, academia, and the government, by reusing prediction data from an existing ABS model, knowledge from existing ontologies and domain pathways. By acquiring and analyzing data from various sources, researchers and decision-makers can gain massive amounts of beneficial information, for example, to understand domain requirements, improve service quality and mitigate risks. Despite being built from scratch, the information gathered for the development of OCMH-S is not new, all the data and information are straightforwardly obtained. OCMS-H is built upon the knowledge gathered and establishes a generic structural framework for organizing data and information in modeling a simulation.

This study contributes to the idea of modeling a simulation in complex domain by attaining the optimal knowledge of the domain with the semantic representation. The hybrid approach can improve the translation of real-world knowledge to model representation, increasing the chances of getting the correct simplification of the domain by making the domain assumptions explicit and provides better interoperability and reasoning capability. The novelty of this model lies in the hybrid ontological model for simulation modeling where it combines DES-based ontology with data from an ABS model to provide deeper context with better accuracy of the pandemic situation. For evaluation purposes, the accuracy of OCMS-H is compared against the National Institute for Health and Care Excellence (NICE) pathways. This paper is structured as follows: Section 2 provides the background of the research topic through a literature review. The methodology of the research is outlined in Section 3. Section 4 describes the domain area of this study. Section 5 highlights the main components of the OCMS-H framework, detailing each of the framework components. Finally, Section 6 provides a discussion and concluding remarks for the framework.

2 LITERATURE REVIEW

This section discusses relevant work from simulation in emergency departments, conceptual modeling and ontology, formal concept analysis, and a hybrid methodological approach and its advantages for advantageous for the healthcare sector's during the Covid-19 pandemic crisis. Healthcare is recognized as a complex and heterogeneous system operating in an unpredictable environment (Aringhieri et al. 2017). The lack of understanding about how the disease spreads and how it affects patients adds to the confusion (Bai, Brunner, and Gerstmeyr 2020). Simulation is a powerful quantitative instrument for the analysis of complex systems, and can be used in tandem with other statistical techniques in an unsteady environment (Garcia-Vicuña, Mallor, and Esparza 2020). The Covid-19 crisis has resulted in an extraordinary competition of decisions between rescuing overburdened healthcare systems and reviving a paralyzed economic productivity. The role of hybrid approach is even more vital within the realm of modeling pandemic related decisions (Lather and Eldabi 2020).

The hospital Intensive Care Unit (ICU) admission policy gap study conducted by Bai, Brunner, and Gerstmeyr (2020) delves further into modeling ICU control rules in order to improve decision-making. Petrović (2020) illustrates how efficient resource allocation during the Covid-19 crisis may be replicated using a combination of environment simulation, deep learning, and linear optimization. Numerous simulation-related studies in the healthcare industry have been presented in recent years. Mahmood et al. (2020) study on the Flu And Coronavirus Simulator (FACS) demonstrates how the simulator can be used to mimic the Covid-19 outbreak pattern and forecast the number of outcomes that can be utilised to generate early alerts for quick emergency response management. DES model study established a new simulation framework for predicting the short-term requirement for vital resources to offer healthcare to Covid-19 patients (Garcia-Vicuña, Mallor, and Esparza 2020). Shanaa and Abdallah (2020) argued that ABS could provide a wealth of data on individual isolation, mobility, and travel isolation in order to forecast the pattern of the COVID19 outbreak. Mesabbah and McKeever (2018) demonstrated a generic and automated end-to-end DES framework by modifying a few parameters and adding additional resources to the system.

The research resulted in an accurate and unbiased simulation model that was enhanced using the DES engine as the foundation for the new framework.

As often, simulation models are created to fulfil a specific set of modeling objectives or to provide an answer to a certain set of questions. A critical initial step in simulation modeling is defining the model's objective. Ontological analysis has been proved to be an effective first step in the development of strong knowledge-based systems capable of modeling simulations. Turnitsa and Tolk (2006) defined ontology's application to simulation modeling. The usages include establishing the domain's definition and process, guiding decision-making, and providing a centralised repository for information. Ontologies are primarily meant to help the systems' users; they serve as the development specification for Saghafian et al. (2015) and provide meaning for knowledge-based systems (Tolk et al. 2015). According to a study conducted by Maryasin (2019), ontologies significantly simplify data interchange between embedded models and the digital twin's service programmes, as well as between the digital twin and external agents, users, or other applications.

While an ontology network is defined as an appropriate approach for developing, integrating, maintaining, and managing a collection of interrelated ontologies (Detoni et al. 2017), ontology-driven conceptual modeling is defined as a model that was designed in a systematic manner to confirm an underlying ontological theory (Guizzardi et al. 2019). According to Guerson, Sales, Guizzardi, and Almeida (2015), validating an ontology entails determining whether a given model is the correct model for a domain. Bao and Xia (2017) developed a hybrid algorithm based on an ontology approach to improve the performance of searching for more appropriate services with a higher degree of accuracy, in order to facilitate decision-making and planning. Ontologies can be enhanced in a variety of ways by referencing to existing ones. In a research by Guerson, Sales, Guizzardi, and Almeida (2015) stated that OntoUML Lightweight Editor provides visual simulation and ontological anti-pattern management. The authors concluded that by employing OntoUML models, any UML tool that allows stereotype can be used virtually. According to Isern et al. (2016) survey, the main usage of ontology in ABS model in healthcare is the usage of ontological representations of medical staff and patients and their dependencies. Typically, ABS models make use of shared ontologies among system entities.

Silver et al. (2011) introduces four first-level subclasses for discrete-event simulation models based on the DES principle: state-oriented model, event-oriented model, activity-oriented model, and process-oriented model. In recent years, hybrid models have been been getting traction and was implemented in a variety of domains. It has been argued by many researchers that hybrid approach in simulation modeling for healthcare domain provides better insights into the real-life system as it allows modelers to look into issues from multiple perspectives. Huang et al. (2020) demonstrate and idea of combining two distinct approaches to obtain more reliable forecasts for medical service demand forecasting that maintain high prediction accuracy as the prediction horizon increases concurrently found that the hybrid prediction model demonstrated a significant improvement in both prediction accuracy and prediction horizon. Accurate forecasting in medical services would be advantageous during a critical pandemic crisis, as it would allow for optimal allocation of human and physical resources, benefiting both healthcare providers and patients (Xu et al. 2016).

3 RESEARCH METHODOLOGY

The OCMS-H framework is an enhanced and customized version of the Minimal-Viable Simulation Ontology (MVSimO) introduced by Saleh and Bell (2021). The key approaches of MVSimO are the domain conceptualization that leads to modules identification and candidate ontologies selection to determine the abstracted and simplified simulation to be modeled under DES settings. The derived components from the process are then analysed using Formal Concept Analysis (FCA) by Wille (1982) to find dependencies between attributes and processes in emergency departments. These findings are then used to develop a minimal and viable ontology, MVSimO through the method of event scoping and event harmonization from a framework by Bell et al. (2007). MVSimO dives into DES perspective to reflect emergency departments pathways where the movement of patients are taking place. Based on Günal and Pidd (2009), DES is suitable to be used under the assumption that it is the preferred simulation modeling technique since it demonstrates a complex environment where events occur in sequences. The study does not consider influencing factors affecting patient movement. It focuses on physical resources and internal systems performed from check-in, assessment, treatment and outcomes. Data gathered during the development of MVSimO are static data from existing ontologies and history records of patient admission at a National Health Service (NHS) hospital.

Healthcare sectors need to prepare for the emergency response against the Covid-19 outbreak effectively. For example, a locally informed model to observe important components of the pandemic by Davies et al. (2020) observes hospital impact model with epidemiological setting in Covid-19 Hospital Impact Model for Epidemics CHIME. Other studies that include the non-pharmaceutical interventions (Davies et al. 2020) and analyzing the spatial datasets (Mahmood et al. 2020) are conducted to combat Covid-19. For this reason, this study aims to improve MVSimO by making use of important data insights from a prediction model (like geospatial data, epidemiology data, demographic data and interventions undertaken data) to show the impacts of Covid-19 in healthcare. To do this, real-time prediction data from FACS, a geospatial agent-based simulator for analyzing Covid-19 spread and public health measures on local regions (Mahmood et al. 2020) model, will be analyzed to search for important elements to construct OCMS-H. By incorporating data from FACS, this study is able to provide a more accurate ontological representation model of emergency departments during the pandemic where the processes in the departments are represented by the DES paradigm and the impact factors of COVID-19 to healthcare are captured through the ABS environment.

4 CASE STUDY

The Covid-19 pandemic has stretched hospital resources all over the world, especially the emergency departments. Generally, the department is one of such high exposure facilities as the departments are on the front lines, serving an essential function in identifying Covid-19 patients, separating them from other patients whilst providing urgent treatment. In the UK, efforts are being taken to flatten the curve so that the NHS would be able to care for sicker patients and provide all the assistance needed. Non-pharmaceutical interventions like lockdown with social distancing, occupy home message and advice to wash hands regularly were introduced to curb the spread of the virus. Figure 1 as presented in the project "*A Better A&E*" by PearsonLloyd shows patient flows in emergency departments - from movements of patients from check-ins, to assessment, treatment and outcomes. The processes indicate a sequence of steps that DES could represent. DES models emergency departments pathways as networks of queues and activities, where state changes in the system occur at discrete points of time.

The modelers develop an ABS to manifest the relationships between the model elements and their behavioral rules. In most agent-based models, the aim is to develop sensible rules at the agent level to an extent when the model runs, it will replicate the scenario in emergency departments. An example of this is Mahmood et al. (2020) which sets out to model the spread of Covid-19 and public health measures that focus on Covid-19 transmission within the context of a town, small city, or borough. It combines disease properties, geospatial information and basic demographic information to predict the number of infection and hospitalization rates across the area. This paper points out the hybridization approach by combining ABS derived outputs as inputs for a DES pipeline for a more precise definition of the domain through ontology.

5 THE OCMS-H FRAMEWORK

Ontology in simulation has been seen as a conceptual model of a system explicitly and unambiguously, can be applied to better capture the modeler's perspective of the domain. Regarding an ontology for simulation modeling, reusing ontologies help to reduce time and effort in attaining the domain knowledge, and at the same time, assist in domain understanding. For this reason, this study reuses existing ontology in the first

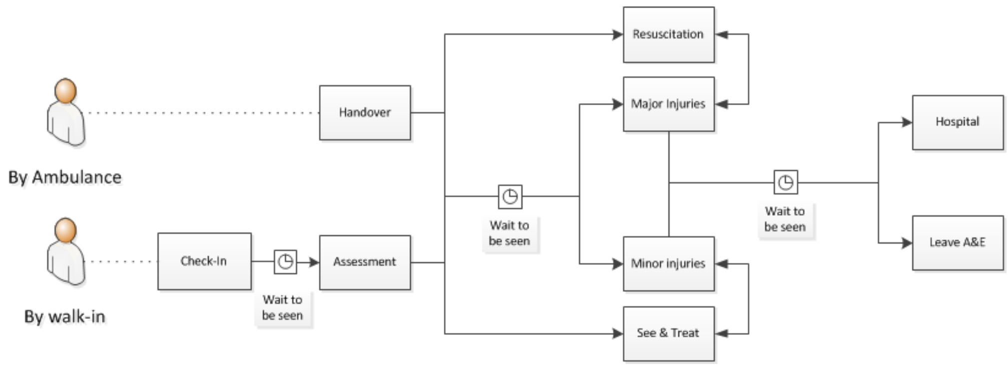

Figure 1: Emergency Departments or A&E Process Flow.

stage of development. The generic model of MVSimO (Saleh and Bell 2021) outlines a baseline to represent discrete events that occur in emergency departments. By adopting MVSimO, this paper attempts to validate the research theory, that reusing structured domain knowledge as modules to represent sub-ontologies may lead to the building of a new ontology. It contributes to an improved ontology reuse framework.

The decision to reuse fragments of ontologies from existing ontological sources is one of the activities performed in an ontology engineering process (Simperl 2010). As pointed out by Lonsdale et al. (2010) "*Ontology reuse involves building a new ontology through maximizing the adoption of pre-used ontologies, or ontology components*". Given all that has been mentioned so far, it emphasizes that ontology reuse is an integral part of this study. In the following sections, the ontology improvement will be described. Apart from MVSimO reuse, data streamed from the ABS model, FACS is used as domain knowledge to support the development of OCMS-H. This hybrid approach aims to provide taxonomies for a sequence of events in emergency departments and at the same time reflects the behaviour of the disease that has been modeled. This could increase the proposed model capabilities and reduce any limitations from a single approach. Figure 2 shows the overview of the proposed framework.

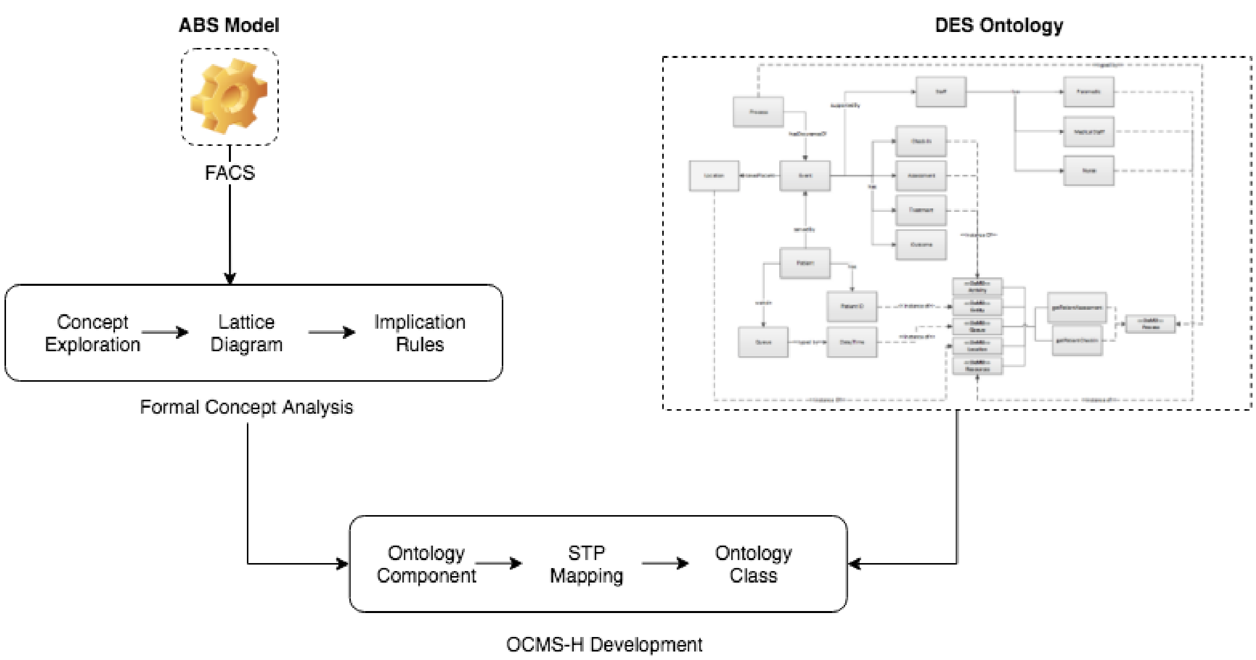

Figure 2: The OCMS-H Framework.

5.1 DES ONTOLOGY & ABS MODEL

As shown in Figure 2, we utilize MVSimO from Saleh and Bell (2021) as our baseline ontology for DES. The definition of MVSimO is adopted from the definition of Minimal Viable Product by Ries (2009): "*the version of a new product which allows a team to collect the maximum amount of validated learning about customers with the least effort*". Reflecting this, learning outcomes collected from MVSimO uphold the execution of this study. And for an ABS model, we use FACS from Mahmood et al. (2020) to showcase the impact of Covid-19 through simulation. The hybridization process starts by extracting ontology elements from the first-cut of MVSimO ontological commitment (Figure 3). Few MVSimO classes are selected for this study. Initially extracted from the Ontology for Discrete-Event Modeling and Simulation Ontology (DeMO), *Activity*, *Entity*, *Queue*, *Location* and *Resources* classes are selected to represent the *getPatientAssesment* and *getPatientCheckIn* under the *Process* class. *getPatientAssesment* and *getPatientCheckIn* events were derived from rigorous processes to build a semantically rich ontological model. The following subsections present a more detailed description for each component of the OCMS-H framework, supported by a detailed description of the dataset supplied by the ABS model.

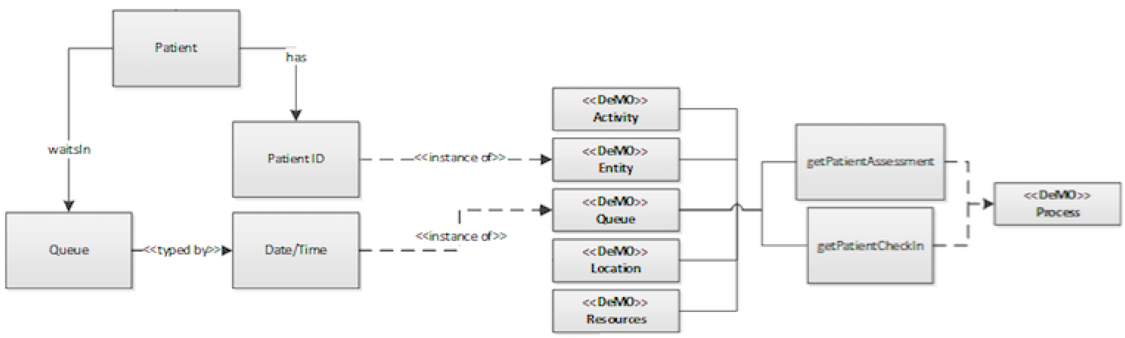

Figure 3: The First-cut of MVSimO.

5.2 FORMAL CONCEPT ANALYSIS

In this study, FCA is used to support the semantic notation from existing ontology, MVSimO. FCA was first introduced as a mathematical perception for concept formalization and conceptual thinking by (Wille 1982). The study by Obitko et al. (2004) discussed the process of designing an ontology using Formal Concept Analysis. The method initiated ontology design by implying the hierarchy of relevant concepts and described the concepts as class properties. FCA analyzes the dependencies between a set of objects and a set of attributes (Davey and Priestley 2002). Not only describing the dependencies between attributes, the hierarchical property of concept lattices in FCA also makes a good foundation in defining the structural property of the applied domain (Kuznetsov and Poelmans 2013). FCA produces results in two sets of output data. The first set is a list of all the interdependencies or rules among the attributes in the *formal concept* named implications set (See Figure 4). The second set is a hierarchical relationship of all the established concepts of the domain known as the *concept lattice* (See Figure 5). The followings are the formal definitions of FCA:

- **Definition 2.1** Formal context
  A formal context is a triplet *(X, Y, I)* where X is a set of objects and Y is a set of attributes and I is a binary relation between X and Y, i.e., $I \subseteq X \times Y$. $(x,y) \in I$ indicates that the object x has attribute y.
- **Definition 2.2** Intent and Extent
  Let (X, Y, I) be a context, X' $\subseteq X$ and Y' $\subseteq Y$, the function Intent maps a set of objects to the set of

attributes, whereas the function Extent maps a set of attributes to the set of objects:
Intent (X') = y $\in Y'$ — $\forall y \in Y'$, (x,y) $\in R$
Extent (Y') = x $\in X'$ — $\forall x \in X', (x,y) \in R$
For X' $\subseteq X$, Intent (X') is the set of attributes owned by all objects of X', and Extent(Y') is the set of all objects that own the attributes Y'. The two functions form a Galois connection and formal concepts.

- **Definition 2.3** Formal Concept
  A Formal Concept C in a context is a pair (X', Y') that satisfies Y' = Intent (X') and X' = Extent(Y') i.e., C is a Formal Concept $\Leftrightarrow$ for X' $\in CandY' \in C$, Extent(Intent(X')) = X',
  and symmetrically, Intent(Extent(Y')) = Y'.
- **Definition 2.4** Implications
  An implication A $\Rightarrow B$ holds in (X,Y,I) if and only if B $\subseteq A$", which is equivalent to A' $\subseteq B$'. It then automatically holds in the set of all concept intents

The conceptual exploration method from FCA is conducted using data from the FACS model. This exploration manages to show the relationships between agents' behavior when dealing with Covid-19 pandemic. Data consist of 100 objects (timestamps) and 7 attributes (exposed, infectious, dead, number of infections by day, number of hospitalization by day, hospital bed occupancy) mapped as 'X' value into the cross table as formal context. 'X' is mapped into if there is an increase from a day-to-day basis. In a cross-table, associating an object to the attributes created a concept hierarchy that can be visualized using the concept lattice. Figure 4 shows a cross-table where formal contexts are mapped with ConExp software using data from FACS. The cross-table describes formal context existed in FACS data as per described in **Definition 2.1**. The little circles in Figure 5 represent the 49 concepts of the context and the ascending paths of line segments represent the subconcept-superconcept-relations (such as path may change its direction at a meeting of lines only if there is a little circle or a dot). The definition of concepts is explained in **Definition 2.3**.

A	B	C	D	E	F	G	H
	exposed	infectious	recovered	dead	num infections today	num hospitalisations today	hospital bed occupancy
Time 1							
Time 2	X	X	X		X	X	X
Time 3	X	X	X		X		
Time 4	X	X	X		X	X	X
Time 5	X	X	X		X		
Time 6	X	X	X	X	X	X	X
Time 7		X	X				
Time 8	X	X	X		X		
Time 9	X	X	X		X	X	
Time 10		X	X	X	X		
Time 11	X	X	X		X		
Time 12	X	X	X		X	X	X
Time 13	X	X	X		X		X
Time 14		X	X	X	X	X	
Time 15	X	X	X	X	X	X	X
Time 16		X	X			X	X
Time 17		X	X	X			X
Time 18	X	X	X	X	X		X
Time 19		X	X				X
Time 20	X	X	X	X	X	X	X

Figure 4: Formal Context in Cross Table.

The dependencies between the attributes, i.e. attribute implications or association rules are also generated using ConExp. From 34 association rules generated, only 11 rules with clear implications between the attributes in the formal context (with confidence of 100%) are selected. The set of implication rules are generated to show a set of agents' behavior when dealing with Covid-19 pandemic. The list of implication rules below represent list of agents' behavior. By applying FCA approach to capture agents' behavior, we learnt that OCMS-H could potentially provide more details into simulation modeling paradigm.

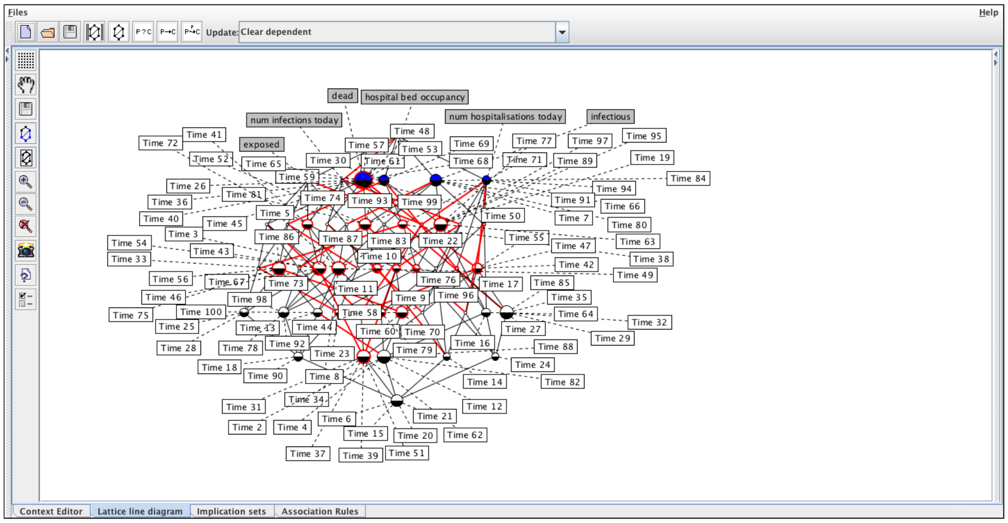

Figure 5: Concept Lattice of FACS Data.

- **Rule 1** increase in exposed, infectious, number of hospitalization implies increase in number of infections
- **Rule 2** increase in number of infections, hospital bed occupancy implies increase in exposed
- **Rule 3** increase in exposed, number of hospitalization, hospital bed occupancy implies increase number of infections
- **Rule 4** increase in exposed, dead, number or infections, number of hospitalization, hospital bed occupancy implies increase in infectious
- **Rule 5** increased in exposed, dead, number of infections, number of hospitalization implies increase in hospital bed occupancy
- **Rule 6** increased in exposed implies increase in recovered
- **Rule 7** increased in infectious implies increase in recovered
- **Rule 8** increased in dead implies increase in recovered
- **Rule 9** increased in number of hospitalisation implies increase in recovered
- **Rule 10** increased in number of infections implies increase in recovered
- **Rule 11** increased in number of hospital bed occupancy implies increase in recovered

6 DISCUSSION AND CONCLUSION

In the era of Covid-19, medical resources allocation is becoming increasingly important to the management of healthcare service providers, as it is directly linked to the timely supply of medical services. Hence, accurate forecasting is essential (Huang et al. 2020). The completeness and intensiveness of the future simulation model could be gained through MVSimO elements and the rules generated from the FACS model. OCMS-H has the utility as a conceptual model to ensure that it can handle the behaviours and interactions of the domain's constituents. To suppport this claim, OCMS-H asserts to have more elements as compared to NICE pathways of Chronic Obstructive Pulmonary Disease (COPD) (see Figure 6). COPD pathways are chosen as a comparison because the clinical symptoms such as respiratory distress of Covid-19 and acute COPD is difficult to differentiate (Lippi and Henry 2020) which may potentially result in delayed or inappropriate medical intervention (Zhao et al. 2020).

As a conclusion, OCMS-H acts as a framework that is assumed to play a role in setting up a common ground of modeling a simulation in emergency departments during the Covid-19 pandemic. OCMS-H is developed to provide an infrastructure of knowledge sharing among subject domains and describes, standardizes and represents objects or instances in the domain. Due to the complexity and ongoing work

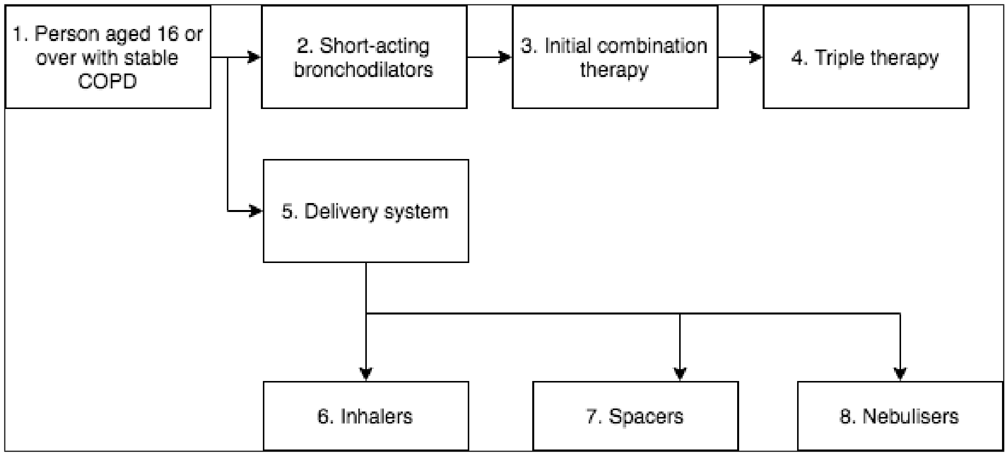

Figure 6: NICE Pathways - Chronic Obstructive Pulmonary Disease.

required to merge ontology components and process elements from the STP map into complete OCMS-H classes, the full evolution of OCMS-H will not be addressed in this paper. Only the section on ABS model-FCA and DES ontology are outlined. As shown in this study, OCMS-H has the potential to elevate modeling of simulation in emergency departments to a level of detailed abstraction. The first steps have been taken in this direction by developing a complete a full model of OCMS-H in a formal ontology language, and the utility of the approach will be demonstrated by building a moderately complex simulation model of emergency departments. This could later help in policy-making for the planning and allocation of healthcare resources.

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