Planning medical oxygen supply distribution to treat hospitalized COVID-19 infected patients

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Abstract

The recent novel coronavirus disease (COVID-19) outbreak caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) currently poses a threat to public health as it rapidly spread over the globe leading to a worldwide pandemic. This highly contagious disease usually manifest respiratory disorder in infected patient and, in severe cases, the patients must be put on an oxygen supply or mechanical ventilator to help them breathe. However, hospitals from different nations, particularly in developing countries, faced issues with medical oxygen shortages due to an overwhelming number of patients and, in some cases, poor public administration. Risks of public healthcare breakdown such as this can be reduced through risk assessment and management. The use of automated planning and disaster response modeling allows a practical approach to help reduce the chances of oxygen crisis in health systems. This paper details a PDDL+ planner designed to estimate the medical oxygen distribution to treat respiratory diseases in healthcare units. The developed planner is capable of estimating the oxygen levels demanded by hospitals, the oxygen production capacity inside factories, and the means of transportation required to deliver the oxygen tanks.

The severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) was first reported in Wuhan, China in December 2019 (Chen et al. 2020). SARS-CoV-2 is the virus responsible for the COVID-19, a contagious disease that can cause severe respiratory illness. Since then, the coronavirus disease 2019 has spread all over the globe becoming a worldwide health challenge. The COVID-19 pandemic and the social distancing measures have already resulted in a critical impact on socio-cultural, political, and economic aspects of our society (George, Lakhani, and Puranam 2020).

The COVID-19 has put intense pressure on health-related systems and increased the already existing demand for medical oxygen therapy. Many hospitals, especially in developing countries that already struggled before the pandemic to meet their daily oxygen needs, suffered from oxygen shortages (Jones 2020). As a result of this crisis, a desperate situation rapidly emerged within hospitals, patients, and patient family members due to the critical status of oxygen as a vital approach for treating COVID-19 infection cases (Usher 2021).

Due to pandemic proportions, several modeling approaches have been introduced to help simulate and counteract the effects of COVID-19 in the global population. COVID et al. 2020 developed a deterministic SEIR (susceptible, exposed, infectious, and recovered) compartmental framework to provide a state-level epidemiological analysis of the SARS-CoV-2 infection across the United States. Observations from the first recorded case in the U.S. (1 February 2020) to 21 September 2020 were used to estimate the effects of non-pharmaceutical intervention strategies such as social distancing and mask use. The study pointed out that the use of face masks by 95% of the population could be sufficient to minimize the worst effects of epidemic resurgences in many states. Oliveira et al. 2021 created a compartment model named SEIIHURD that, based on the data from the first wave of COVID-19 in Brazil, estimated the number of beds required to attend the population in the state of Bahia, Brazil. The model considered the transmission of the virus by asymptomatic/mild cases, hospitalization of severe cases, and mortality to evaluate the responsiveness of the state health services in terms of the number of beds. Although the current advances, no models have been designed to plan and estimate the minimal oxygen thresholds required in hospitals to help avoid the collapse of health systems due to crisis and shortage of medical oxygen therapy.

Planning is an area in Artificial Intelligence (AI) that concerns the course of actions needed to achieve a specific goal, optimizing the agent's performance (Ghallab, Nau, and Traverso 2004). More specifically, the classical planning seeks to identify a sequence of actions, also known as a plan, that drives the initial state of this particular problem to the goal state (Fox, Long, and Magazzeni 2017). An AI planning system, or planner, takes the problem formalisation as input and constructs complex plans of actions to reach the most optimal problem solution. The Planning Domain Definition Language (PDDL) is a standard encoding language for automated planning tasks and is widely adopted by planning systems (Borgo, Cashmore, and Magazzeni 2018). To better represent mixed discrete-continuous domains, an extension of PDDL named PDDL+ was created which incorporates fully-featured autonomous processes allowing a more precise tool for modeling (Batusov and Soutchanski 2019).

The PDDL+ is planning language used for modeling mixed discrete-continuous planning domains (Fox and Long 2006). So far, several heuristics and planners were developed for PDDL+ (Della Penna et al. 2009; Bryce et al. 2015; Scala et al. 2016). In this context, this paper details the usage of automated planning techniques through PDDL+ to solve the paradigm of medical oxygen distribution to treat respiratory diseases. The Expressive Numeric Heuristic Search Planner (ENHSP) and the A^* as search engine heuristic, an interval-based relaxation (Scala et al. 2016) were used to formalise the domain and problem.

Formalization

The PDDL formalization of a problem consists in general of two parts: the domain description and the problem definition. The same structure applies to PDDL+ however, the language additionally supports features for numeric planning. Thus, in PDDL+ the domain contains the actions, states, functions, and predicates about the problem. Meanwhile, the problem defines the initial state of the environment and goal state which must be reached through planning. The following subsection describes both the domain description and problem description developed for this study.

Domain Description

Initially, the domain description defines the domain and `:requirements` that calls for components that will be used within the domain. `:predicates` and `:functions` defines the properties of objects and are used to encode the state variables. The `:predicates` return either true or false while the `:functions` express numeric assignments. The developed model is composed of the following predicates and functions:

Predicates

- `(connected_road ?x ?y)`: defines a road connection between *x* and *y*;
- `(connected_airway ?x ?y)`: defines a airway connection between *x* and *y*;
- `(oxygen_location ?fact ?x)`: defines the where the oxygen tanks were originated and the current location;

Functions

- `(num_patients ?h)`: number of patients in a hospital *h*;
- `(oxygen_per_person)`: how much oxygen ($liters3$) a person needs;
- `(hospital_oxygen ?h - hospital)`: how much oxygen ($liters3$) is in a hospital *h*;
- `(required_oxygen ?h)`: the total amount of oxygen ($liters3$) demanded by a hospital *h*;
- `(daily_oxygen_volume_produced_per_machine ?f)`: the daily production capacity of a single oxygen generator of a factory *f*;
- `(num_machines ?f)`: number of oxygen generators in a factory *f*;
- `(fact_oxygen_production_capacity ?f)`: The total production capacity of a factory *f*;
- `(payload)`: The payload size of the oxygen tanks coming out from the factory;
- `(carrying ?t)`: how much a transport *t* is carrying;
- `(distance ?x ?y)`: the distance (km) between *x* and *y*;

Lastly, the `:actions` details actions that can change the current state of the represented world. In PDDL+, the actions can contain a combination of functions, constants and numerical operators (*, /, +, −, >, <, =, etc). The developed PDDL+ planner contains in total 7 actions. Initially, the action `calculate_oxygen_required` calculates the required total amount of oxygen for a specific hospital *h* through the number of admitted on this hospital and the volume of oxygen a single person consumes. The planner than identifies which factories can provide the oxygen amount required by the action `oxygen_production_capacity`. This action estimates the production capacity in a factory *f* by multiplying the total number of oxygen generator and their individual capacity of production. After doing that, a third action named `load_oxygen_transportation` loads a transportation *t* with the oxygen supply payload for shipment.

Three actions details the means for transportation that includes `transport_truck_local`, used to transport cargo for distances smaller or equal to 100 km, `transport_truck_intercity` required when distances is higher than 100 km but smaller than 500 km and, lastly, `transport_plane` required when transporting cargo for more than 500 km. These actions cause an effect that leads to the movement of the oxygen tanks, originally located in `x` to a connected point `y`. As an example, the code below details the action `transport_plane`, a similar structure is used for the other two transportation actions.

```
(:action transport_plane
  :parameters (?x ?y - location ?h - hospital ?f - factory ?t -
       airplane)
  :precondition (and
   (< (hospital_oxygen ?h) (required_oxygen ?h))
   (connected_airway ?x ?y)
   (> (distance ?x ?y) 500)
   (oxygen_location ?f ?x)
   (> (payload) 0)
  )
  :effect (and
   (assign (carrying ?t) (payload))
   (not(oxygen_location ?f ?x))
   (oxygen_location ?f ?y)
  )
)
```

Listing 1: Formalization of transportation of oxygen supply through airplane

Lastly, the action `deliver_oxygen` is responsible for delivering the required amount of oxygen supply to the respective hospitals. The action preconditions require that the transport is located in the hospital and, as an effect, it unloads the cargo from the transport *t* and assigns the same amount to the total amount of oxygen in the hospital *h*.

```
(:action deliver_oxygen
  :parameters (?f - factory ?h - hospital ?t - transport)
  :precondition (and
    (< (hospital_oxygen ?h) (required_oxygen ?h))
    (> (carrying ?t) 0)
    (oxygen_location ?f ?h)
  )
  :effect (and
    (assign (hospital_oxygen ?h) (carrying ?t))
    (assign (carrying ?t) 0)
  )
)
```

Listing 2: Formalization of the delivery oxygen method

Problem Description

The problem description is composed of `(:objects)` that details the objects of the problem, `(:init)` that details the initial conditions of the problem, and `(:goals)` which describes the goal states that must be achieved. The objects in this work refer to the means of transportation and the entities hospital, airport, and factory. The initial states about this problem include a description of the road and airway connections between entities, the number of patients admitted to each hospital, the amount of oxygen to keep those patients alive, and the production capacity of factories including machinery and production time.

Experiments and Results

Two experiments were created. The first problem description was created to represent a real case scenario of public healthcare collapse that occurred in Manaus, Amazonas - Brazil in January 2021 due to a lack of oxygen tanks in hospitals. The Brazilian government, in order to suppress the oxygen supply crisis in Manaus, sent through military cargo airplanes with oxygen tanks from Belém, Pará - Brazil. This scenario was detailed in the problem description to assess if the planner was able to deliver oxygen tanks to one of the most affected hospitals by the shortage of oxygen supply in Manaus. Figure 1 shows the routes and problem-solving options.

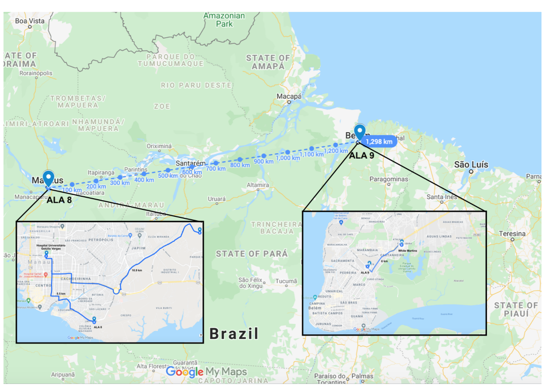

Figure 1: Representation of the problem description for the delivery of oxygen supply for a Hospital in Manaus, Amazonas - Brazil that suffored with oxygen supply crisis in January 2021

The problem description was defined with a total of one hospital (Hospital Universitário Getulio Vargas, Manaus), two airports (Brazilian air force base ALA8, Manaus and Brazilian air force base ALA9, Belém), two oxygen factories (White Martins factory in Manaus and Belém) and the roads and airways that connected them. The simulated factory in Manaus had a lower production capacity compared to the factory in Belém. The planner recognized that the local factory would not dispose of the oxygen volume required by the hospital. Thus, it required a plan involving the transportation of oxygen from the factory in Belem to the hospital. First, the oxygen supply in Belem was moved through a local truck from the factory to the Brazilian air force base ALA9. An airplane transported the oxygen tanks from ALA9 to ALA8. After that, local transportation was used to move the tanks to the Hospital Universitário Getulio Vargas (Figure 2). The time needed to represent this scenario was about 0.02 seconds.

```
Problem Solved
0.0: (oxygen_production_capacity White_Martins_Belem)
1.0: (calculate_oxygen_required Hospital_Universitario_Getulio_Vargas)
2.0: (load_oxygen_transportation White_Martins_Belem Hospital_Universitario_Getulio_Vargas)
3.0: (transport_truck_local White_Martins_Belem Air_Force_base_ALA_9-Belem Hospital_Universitario_Getulio_Vargas White_Martins_Belem truck_local)
4.0: (transport_plane Air_Force_base_ALA_9-Belem Air_Force_base_ALA_8-Manaus Hospital_Universitario_Getulio_Vargas White_Martins_Belem C-130_Hercules)
5.0: (transport_truck_local Air_Force_base_ALA_8-Manaus Hospital_Universitario_Getulio_Vargas Hospital_Universitario_Getulio_Vargas White_Martins_Belem truck_local)
6.0: (deliver_oxygen White_Martins_Belem Hospital_Universitario_Getulio_Vargas truck_local)
```

Figure 2: Problem solution for the delivery of oxygen supply for a Hospital in Manaus, Amazonas - Brazil

A hypothetical scenario was developed to analyze a much broader and complex environment that includes multiple hospitals, airports, and oxygen factories (Figure 3). This problem description consists of: a small-size factory in Porto Alegre, RS - Brazil, and a large-scale factory in São Paulo, SP - Brazil, hospitals in Rio Grande do Sul including Passo Fundo, Carazinho, and Marau, airports in Porto Alegre and São Paulo connected through airways and the roads connecting these entities. Hospitals in Passo Fundo, Carazinho, and Marau had a relatively small oxygen demand while the hospital in Porto Alegre had a significantly larger request.

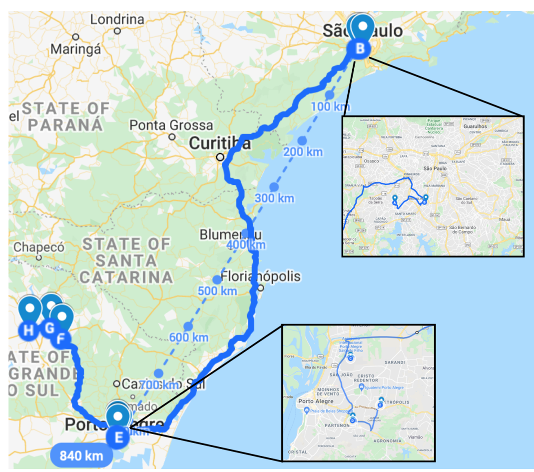

Figure 3: Representation of the problem description for the delivery of oxygen supply in hospitals within Rio Grande do Sul, RS - Brazil

Initially, the planner calculated the exact amounts requested by each hospital and analyzed the factories that could provide the oxygen needed. For the hospitals in Passo

Fundo, Carazinho and Marau the planner identified that the small factory in Porto Alegre was able to produce the required amount. An intercity truck carried the payload from the factory to the hospitals. On the other hand, the request in Porto Alegre was too large for being supplied by the same factory. Thus, the planner selected the factory in São Paulo to provide the oxygen levels required. The oxygen was moved by a local truck from the factory to the airport in São Paulo. After that, the planner used an airway connection to transport the tanks from Sao Paulo to Porto Alegre. Lastly, a local truck carried the oxygen and delivered it to the hospital 4. For this problem description, the execution time was about 0.34 seconds.

```
Problem Solved
0.0: (oxygen_production_capacity factory_Sao_Paulo)
1.0: (calculate_oxygen_required HSL_Porto_Alegre)
2.0: (load_oxygen_transportation factory_Sao_Paulo HSL_Porto_Alegre)
3.0: (transport_truck_local factory_Sao_Paulo CGH_Sao_Paulo HSL_Porto_Alegre factory_Sao_Paulo truck_local)
4.0: (transport_plane CGH_Sao_Paulo POA_Porto_Alegre HSL_Porto_Alegre factory_Sao_Paulo Boeing_747)
5.0: (transport_truck_local POA_Porto_Alegre HSL_Porto_Alegre HSL_Porto_Alegre factory_Sao_Paulo truck_local)
6.0: (deliver_oxygen factory_Sao_Paulo HSL_Porto_Alegre truck_local)
7.0: (calculate_oxygen_required HCC_Carazinho)
8.0: (oxygen_production_capacity factory_Porto_Alegre)
9.0: (load_oxygen_transportation factory_Porto_Alegre HCC_Carazinho)
10.0: (transport_truck_intercity factory_Porto_Alegre HCC_Carazinho HCC_Carazinho factory_Porto_Alegre truck_intercity)
11.0: (deliver_oxygen factory_Porto_Alegre HCC_Carazinho truck_intercity)
12.0: (calculate_oxygen_required HSVP_Passo_Fundo)
13.0: (load_oxygen_transportation factory_Porto_Alegre HSVP_Passo_Fundo)
14.0: (transport_truck_intercity factory_Porto_Alegre HSVP_Passo_Fundo HSVP_Passo_Fundo factory_Porto_Alegre truck_intercity)
15.0: (deliver_oxygen factory_Porto_Alegre HSVP_Passo_Fundo truck_intercity)
16.0: (calculate_oxygen_required HCR_Marau)
17.0: (load_oxygen_transportation factory_Porto_Alegre HCR_Marau)
18.0: (transport_truck_intercity factory_Porto_Alegre HCR_Marau HCR_Marau factory_Porto_Alegre truck_intercity)
19.0: (deliver_oxygen factory_Porto_Alegre HCR_Marau truck_intercity)
```

Figure 4: Problem solution for the delivery of oxygen supply in hospitals within Rio Grande do Sul, RS - Brazil

Conclusion and Future Work

This study is an initial step for estimating the demand for oxygen supply in hospitals and healthcare facilities to help avoid oxygen shortages. The disposal of oxygen is essential for medical oxygen therapy for treating disease that causes shortness of breath such as the novel coronavirus. This planner was developed using PDDL+ language and, ideally, can be used to minimize the risks of health system collapse as a consequence of the lack of oxygen for patient treatment. The A* search heuristic (Scala et al. 2016) utilized in this model had a reasonable response time for solving the given problems. The high scalability of the developed planner allows the definition of problems that can variate according to the area of study. Thus, the system can simulate the demand for oxygen supplies on a local to a regional scale according to the problem complexity.

Future work will incorporate into the source code the transportation capacity for each transportation method. This can allow the evaluation, on a deeper level, further logistics needed for the shipment of oxygen cylinders, for example. Additionally, further exploration is planned to establish a method for representing specific scenarios in which some transportation methods may not be available. The developed tool ultimately seeks to contribute to the reduction of death rates associated with COVID-19.

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