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ABSTRACT

The COVID-19 pandemic has profoundly altered common social and economic patterns as governments all over the world have been forced to take drastic measures to counter the spread of the disease. Among them, quarantine, the closure of borders, and social distancing are the ones that have affected transportation systems most severely. With the clear need to avoid all unnecessary direct human contact, an increased interest in contactless transportation and delivery modes emerged. Drones are a promising alternative in this regard, especially for the delivery of essential goods, such as COVID-19 viral tests. In this study, we therefore investigate how drones can be used to distribute viral tests to potentially infected patients. The novel approach that we propose is to use existing drone infrastructure to perform this task, where drones owned and operated by different public and private entities are retrofitted for the distribution of essential goods in the case of emergency. In a wider sense, we hence suggest the establishment of a drone enabled back-up transport system. Potential performance gains are analyzed through a mathematical time and cost model that was developed in close cooperation with the state Red Cross Organization and a utility drone manufacturer. Process design as well as parameter estimation are based on empirical investigation including, but not limited to, accompanying a COVID-19 mobile testing team in the field. The practical feasibility was verified by retrofitting drones initially assigned to other purposes. Additionally, policy recommendations, such as the establishment of public-public and public-private partnerships, were identified.

1. Introduction

Transportation systems are crucial for the economy as they form the basis of international trade. With increasing complexity and uncertainty, they are however often exposed to risks that potentially cause disruptions and lead to long-term economic harm (Wan et al., 2018). The events causing such disruptions are hard to predict and control. Therefore, the development and implementation of adequate policies, regulatory frameworks and recovery strategies are required to increase transport robustness and resilience (Cox et al., 2011; Miller-Hooks et al., 2012). Past events, such as major volcanic eruptions (Wieland and Wallenburg, 2012), earthquakes (Blake et al., 2019), or floods (Arrighi et al., 2019) have demonstrated the vulnerability of transport networks to external impacts, pointing to the necessity of having appropriate measures at hand. Since December 2019, the world population is once again facing a disruption of unexpected magnitude caused by a newly discovered coronavirus SARS-CoV2. It causes a severe acute respiratory infection (COVID-19), comparable to pneumonia, characterized by fever, cough and shortness of breath (Liu et al., 2020). The first cases were reported to the World Health Organization from China (World Health Organization, 2020b), upon which the virus has spread globally, as it is easily transmitted from person to person (Bai et al., 2020). In consequence, systematic interventions to contain the pandemic were urgently put in place. Many European governments announced nation-wide lockdowns including the suspension of events, the closure of borders and a ban on non-essential movement (Hale et al., 2020). These measures have been accompanied by disruptions to international supply chains and transportation networks. Aside from a dramatic decline in the transportation of goods and people, the extraordinarily high demand for personal protective equipment, masks, COVID-19 tests and other essential goods has caused global supply and transport bottlenecks (Ranney et al., 2020). Particularly, the inevitable need for social distancing to contain the spread of the virus, has led to a surge in online shopping and digitally enabled delivery systems that work without the need for direct human contact (Lin, 2020). As the demand for contactless delivery has grown, autonomous transport technologies,
such as unmanned aerial vehicles or drones, have attracted increased attention from governments, organizations and authorities. The Spanish police for instance, used drones equipped with loud speakers to communicate lockdown measures to citizens (Reuters, 2020) while other countries, including China and the United States, have deployed drones to perform aerial disinfection and the transportation of medical samples (World Economic Forum, 2020).

From a technical point of view, drones are teleoperated flying machines that do not require constant user control. They usually run on batteries and many are capable of carrying additional payload (Vergouw et al., 2016), and consequently they have gained the attention of large companies such as Amazon and UPS (Shavarani et al., 2018). In particular, the retail and parcel delivery industry has been showing interest in making use of the potentials offered by drones when compared to traditional land-based transportation. Currently, the advantages of drones have also attracted the attention of humanitarian organizations, as they allow a more efficient disaster handling (Anbaroglu et al., 2019). Here, drones are predominantly used for disaster response mapping, cargo delivery and search-and-rescue operations (Cui et al., 2015; Karaca et al., 2018). Of special interest for this study are the following advantages of drones. Firstly, their capability to transport items over destroyed, blocked or degraded road infrastructure. In this regard, drones are already in use to deliver urgently needed blood in infrastructure-poor East Africa (Ackerman and Koziol, 2019). Secondly, drones are also used to deliver items in challenging and remote terrain; for example, vaccines in immunization programs in low and middle income countries (Haidari et al., 2016). Thirdly, drones allow the contactless performance of tasks, such as technical inspections (Khakda et al., 2020) or delivery without the need for person-to-person interaction (Li et al., 2017).

Listening to the World Health Organization making an urgent call to drastically increase COVID-19 testing (World Health Organization, 2020c), we propose the use of drones to support and enable testing of potentially infected patients in a decentralized manner. Not only are drones independent in regard to potential on the ground infrastructural issues but, more importantly, they enable a contactless alternative for testing people. With the use of drones, COVID-19 self-test kits and other essential goods can be transported without the need for direct human contact, thus reducing infection risks among involved people. The novel approach that we develop in this study does however not aim at creating new drone fleet capacities, but rather relies on utilizing existing drone infrastructure. Hence, we lay out a pathway to establish a transport approach that we develop in this study does however not aim at creating new drone fleet capacities, but rather relies on utilizing existing drone infrastructure. Hence, we lay out a pathway to establish a transport infrastructure technologically and practically feasible?

To answer these research questions, we clearly identified the need for empirical evidence and therefore established a cooperation with two organizations – the state Red Cross Organization and a utility drone manufacturer. Concerning RQ1, we conducted quantitative research by developing a mathematical cost and time model to compare vehicle-based testing (VBT) and drone enabled testing (DET) in regard to their temporal and financial performance. The corresponding process maps and parameter estimates were collected by accompanying a mobile testing team on the ground while performing COVID-19 tests and through expert information provided by health care professionals and the team of the utility drone manufacturer. For RQ2, we conducted a practical feasibility study of retrofitting a utility drone, originally destined for other purposes, to transport COVID-19 self-test kits. Finally, RQ3 was answered by reconciling model results, practitioner input and existing literature in the field of transport policy development.

The article continues with a review of the existing body of knowledge in the field (Section 2). In section 3, the applied methodology is described and the study outline, parameter estimation along with the developed time and cost functions are introduced. Results of scenario analysis are presented and discussed in section 4. Section 5 provides insights into the feasibility study and section 6 gives an overview of policy implications derived from study findings. The article is concluded with a short synopsis, study limitations and future lines of research (Section 7).

2. Related literature

For the sake of clarity, we have divided our literature review into four parts. First, we summarize literature that quantitatively analyzes drones as an alternative means of transport. After that, we review more practical articles that present results from feasibility studies. Then, we turn to drones in the COVID-19 context and outline preliminary research findings from other scholars. Finally, we consider articles that propose policy implications to facilitate future drone usage.

2.1. Quantitative drone research

So far, scholars have been mainly following the objective to bring new drone-based delivery systems to optimality, which indicates minimizing transport time and costs or maximizing drone delivery coverage (Arambourg et al., 2019; Pan et al., 2020; Chauhan et al., 2019). In that regard, location models allow maximizing service coverage of drone delivery while simultaneously reducing drone energy consumption and minimizing drone logistics costs. Aside from optimal drone hub location, drone routing research has increased over the past few years. Corresponding literature is well documented and very heterogeneous in terms of objectives optimized, solution methods, applications and constraints (Dorling et al., 2017; Li et al., 2017; Rojas Viloria et al., 2020; Coutinho et al., 2018). Another approach to facilitate more time efficient parcel delivery is to pair drones with traditional delivery trucks where a truck loaded with one or several drones travels close to the demand locations, which are ultimately served by a drone. This type of joint routing has been proven to not only yield higher flexibility of delivery systems but to remarkably decrease delivery times and associated costs (see for instance Carlsson and Song, 2018; Chang and Lee, 2018; Hong et al., 2018; Karak and Abdelghany, 2019; Gonzalez et al., 2020; Salama and Srinivas, 2020; Moshref-Javad et al., 2020; Ulin Hernández et al., 2020; Murray and Raj, 2020). Aside from commercial applications, such quantitative approaches can also be found in the humanitarian and disaster-related context. Drones are used for assessing infrastructure damage and last-mile logistics delivery of relief items to remote locations that are inaccessible for land-based transportation (Mosterman et al., 2014; Scott and Scott, 2017; Chowdhury et al., 2017; Rabba et al., 2018; Golabi et al., 2017; Escrivan Macias et al., 2020). Numerous papers have recently been published that put exclusive focus on drone delivery of critical emergency items such as automated external defibrillators (AEDs) for the treatment of people that suffer from sudden cardiac arrest (Zégre-Hemsey et al., 2018; Pulver et al., 2016; Pulver and
2.4. Drone policy implications

First insights into the practicability of drones for AED delivery were generated through a feasibility study by Sanfridsson et al. (2019) who show that bystanders experienced this kind of AED provision as positive, safe and helpful. Other qualitative work by Tatham et al. (2017) focuses on the applicability of drones for medical items delivery and reveals the advantages and challenges inherent in the use of long endurance remotely piloted drones for such purposes. According to the findings, there are numerous infrastructural and organizational obstacles that need to be overcome in order to operationalize drone delivery in post-disaster response. Benefits are mainly represented by the possibility to transport medical items when the terrain is unsuitable for regular road transportation. Thiels et al. (2015) highlight the potentials of drones to transport medical goods (such as blood samples or derivates) to hospitals, mass casualty events and offshore locations in the event of critical demand. By conducting a conceptual analysis, the authors found that drones represent a viable mode of transportation in time-critical situations at significantly lower costs when compared to conventional medical transport.

2.3. Drones and COVID-19

So far, little has been reported on the deployment of drones in the context of infectious disease epidemiology. A brief overview of the current knowledge regarding the use of drones for health care, in particular focusing on infectious diseases, is given by Poljak and Sterbenc (2020). According to the authors, the application of drones has been evaluated in several pilot studies and they are already used for transporting samples, blood, vaccines, medicines, organs and life-saving medical equipment. First practical insights into the application of drones for mapping infectious disease landscapes are provided by Fornace et al. (2014). The authors discuss drones for collecting detailed georeferenced information on environmental factors and other variables that influence the transmission of infectious diseases. They demonstrated the utility of drones to obtain environmental data in two relevant case studies. Another study concentrating on infectious disease mitigation via drones is presented by Hardy et al. (2017). In a proof-of-concept they tested drones for supporting larval source management – i.e. interventions to control and eliminate the transmission of malaria – and mapped water bodies in seven sites across Zanzibar. The authors conclude that drones provide a low-cost and flexible solution to vector-borne disease elimination campaigns. Academic literature that focuses on drones for the specific purpose of COVID-19 containment is extremely scarce. There are only conceptual works available that have evaluated how drones can play a crucial role to support people in quarantine (Estrada, 2020; Skorup and Haaland, 2020). The authors propose drones for monitoring massive epidemic contagious disease spread magnitude, for logistics and cargo delivery and for post-COVID-19 situational monitoring.

2.4. Drone policy implications

While drone policy related research in the military domain is common (Tibori-Szabo, 2015; Ceccoli and Crosston, 2019; Martin et al., 2017; Hazelton, 2017), little has so far been reported on policy implications in the commercial and humanitarian context. A study by Wallace et al. (2018) analyses regulatory responses to the rapid intensification of drone use for wildlife protection. The authors highlight that there are missing policies to address wildlife disturbance in drone regulations and inadequate regulatory capture of environmental impacts of drones on specific geographical areas. A more qualitative study is presented by Thompson and Bracken-Roche (2015), who dedicated special attention to understanding the public opinion about drones in Canada. Through survey analysis the authors aimed at learning more about the awareness of Canadians to use drones for data collection in different application areas. Their findings form the basis for introducing policies that take into account public sentiment and opinion. Graboyes and Skorup (2020) focus on the technical and policy challenges of medical drones in the United States and call for deft regulatory innovations to prevent chaotic situations in future large-scale drone traffic in the US airspace. In particular, they point to current legal drone restrictions, inconsistent drone communication networks, outdated airspace design and privacy and security issues.

By reviewing the vast existing body of scientific literature, it became apparent that a knowledge gap exists concerning the usability of existing drone infrastructure in cases of social, economic or transportation disruptions; as in this case, the COVID-19 pandemic. In that regard, our study can present an interesting approach, as it proposes a new way of tackling bespoke circumstances. Furthermore, the strong practical orientation as well as the derived policy implications can help develop the knowledge base about drone usage for transport related tasks.

3. Methodology

For comparing VBT and DET in regard to their temporal and financial performance, we apply mathematical cost and time modelling. Relevant information for conducting the comparative analysis including parameter estimation and description, estimation of distance travelled and time and cost functions stem from empirical observations, expert discussions and existing academic literature. We started out by analyzing the existing VBT approach applied by the state Red Cross Organization. For this purpose, the second author of this paper conducted expert discussions with health care professionals and accompanied a COVID-19 mobile testing team of the state Red Cross Organization for an entire day shift. Not only was the personal contact with people in charge of testing highly informative, but it also allowed us to gather valuable empirical process information. Aside from practical insights, internal process documents for VBT provided by the state Red Cross Organization were analyzed and formed the basis for subsequent modelling (Austrian Red Cross, 2020). The conceptualization of the DET was conducted in close cooperation with a local utility drone manufacturer. Here, the proposed DET approach was developed during an iterative process where conceptual thoughts were enriched with practitioners’ input. In this chapter, we will first lay out the empirical setting of the study where we describe how the VBT and the DET processes were identified and framed. Then we present the necessary parameters used in the model including the travel distance estimation process. After that, the time and cost functions used for the mathematical analysis are presented, followed by general information concerning the applied model.

3.1. Empirical background

According to the empirical observations and the analysis of internal process documents, the VBT is a standardized process that has to be followed consistently by the mobile testing team with every tested person. The team’s main mission comprises visiting COVID-19 suspects at their homes, to take an oral swab and to deliver the swab sample for post-analysis at a laboratory. The responsible team consists of two health care professionals located at a fixed base station where they serve a 12-h day shift. Dispatching of the testing team is organized by a coordination center that activates them upon request by the local health authorities. A minivan that is customized for the purpose of collecting and processing COVID-19 tests serves the team for driving to the patient sites that are visited in one tour (see Appendix a). When the test team arrives at the patient location, both health care professionals must dress in personal protective equipment that consists of an overall, safety glasses, respiratory mask (FFP3) and gloves. After successful dressing, one of the
health care professionals approaches the patient and informs him/her about the COVID-19 testing process in detail. Next, the patient is tested with an oral swab, which is then placed in a test tube to avoid post-test contamination. In the meantime, the other health care professional who remains outside at the minivan, carries out patient related documentation and prepares for the receipt of the test tube. When the patient testing is completed, the test tube is handed over, labeled with a unique barcode and stored in a cooler. Now, both health care professionals undress themselves following a strict procedure in order to avoid any contact with potentially contaminated personal protective equipment. Due to the high risk of contamination, all equipment elements except safety glasses are disposable products, hence they are thrown away after a single use. Safety glasses have to be collected separately and are reused after disinfection. After completing an entire tour, the final step comprises the disinfection of the minivan, the preparation of the equipment for the next testing tour and personal hygienic measures.

Through the analysis of other scientific sources (Rabta et al., 2018; Wankmüller et al., 2020) and the incorporation of drone expert information, we conceptualized the DET for the distribution process of COVID-19 tests. This approach revolves around the self-sampling of patients and to prepare for the subsequent self-test delivery. However, the drone testing and monitoring is performed by the drone operator, who is trained and equipped with the necessary self-test kits and materials. The drone operator remains outside at the minivan, carries out patient related documentation and prepares for the receipt of the test tube. When the patient testing is completed, the test tube is handed over, labeled with a unique barcode and stored in a cooler. Now, both health care professionals undress themselves following a strict procedure in order to avoid any contact with potentially contaminated personal protective equipment. Due to the high risk of contamination, all equipment elements except safety glasses are disposable products, hence they are thrown away after a single use. Safety glasses have to be collected separately and are reused after disinfection. After completing an entire tour, the final step comprises the disinfection of the minivan, the preparation of the equipment for the next testing tour and personal hygienic measures.

Table 1

| Notation         | Description                                      | Estimates          | Sources                      |
|------------------|--------------------------------------------------|--------------------|------------------------------|
| $d_{ij}$         | Vehicle distance between locations $(i, j = 0, 1, \ldots, n)$ |                    |                              |
| $d_i$            | Drone distance to location $(i = 0, 1, \ldots, n)$  |                    |                              |
| $n$              | Number of patient locations $n \in \mathbb{N}$     |                    |                              |
| $x_i$            | Binary variable $x_i \in (0, 1)$                 |                    |                              |
| $v_v$            | Velocity of vehicle $40$ km/h Health care professional/Empirical observation |                    |                              |
| $v_d$            | Velocity of drone $80$ km/h Drone expert          |                    |                              |
| $v_a$            | Ascent/descent velocity of drone $12.6$ km/h Drone expert |                    |                              |
| $h$              | Operating altitude of drone $0.07$ km Drone expert/Legal source |                    |                              |
| $l_c$            | Labor cost of vehicle crew $60$ €/h Legal source  |                    |                              |
| $l_d$            | Labor cost of drone operator $40$ €/h Drone expert |                    |                              |
| $C_v$            | Operating cost vehicle $0.42$ €/km Legal source   |                    |                              |
| $C_d$            | Operating cost drone $0.15$ €/km Drone expert     |                    |                              |
| $d_{to}$         | Takeoff energy cost fraction drone $1.25$ dml Drone expert |                    |                              |
| $e$              | Landing energy cost fraction drone $0.9$ dml Drone expert |                    |                              |
| $c_o$            | Personal protective equipment cost $31$ € Health care professional |                    |                              |
| $c_d$            | Disinfection cost vehicle $5$ € Health care professional |                    |                              |
| $c_{dr}$         | Disinfection cost drone $0.5$ € Drone expert      |                    |                              |
| $t_m$            | Testing time mobile kit $20$ min Health care professional/Empirical observation |                    |                              |
| $t_{st}$         | Testing time self-test kit $10$ min Empirical observation |                    |                              |
| $t_{hand}$       | Test handover time $0.5$ min Health care professional |                    |                              |
| $t_{dis}$        | Disinfection time vehicle $20$ min Health care professional |                    |                              |
| $t_{dr}$         | Disinfection time drone $5$ min Drone expert      |                    |                              |
| $t_{load}$       | Loading and unloading drone $0.5$ min Empirical observation |                    |                              |
| $t_s$            | Startup time drone $2$ min Drone expert/Empirical observation |                    |                              |
| $t_{sw}$         | Battery swap time $1$ min Empirical observation   |                    |                              |

3.2. Parameter estimation and description

The next step towards building the time and cost model was the identification and estimation of necessary model parameters. In this regard, existing studies by Valerdi (2012), Rabta et al. (2018) and Chowdhury et al. (2017) were consulted for guidance. Additionally, we relied on the evidence gained through expert discussions and the analysis of legal and scientific documents. The estimated and described drone related technical parameters are based on one drone model. For future analysis in different settings, parameters can easily be adjusted accordingly. The parameters as well as descriptions, estimates and sources are listed in Table 1.

The first set of parameters addresses the movement of both the vehicle and the drone, where $v_v$ is the average velocity of the vehicle during non-emergency health operations based on practitioner estimations and empirical observations. While the maximum horizontal velocity of the considered drone model is $90$ km/h, $80$ km/h is a more probable estimate of $v_d$ according to expert judgement. The vertical velocity $v_a$ of the considered drone model is the same for ascent and descent; while $h$ is the assumed flight altitude for the drone under regard. The maximum legally allowed altitude is $150$ m, but $70$ m is enough to clear any manmade or natural structure in the area where this study was conducted.

The second set of parameters considers the costs of performing the corresponding tasks. In this regard, $l_c$ is an estimate of the hourly labor cost for two health care professionals on one vehicle based on the
Austrian collective bargaining agreement. The $b$ parameter is an estimate of the hourly labor cost for one drone operator based on expert information. The official Austrian rate that covers all vehicle related costs (e.g. gas and maintenance) is 0.42 €/km and it was set as an estimate for the operating cost of the vehicle per kilometer ($c_o$). Concerning the drone, $c_d$ is the operating cost of the considered drone model per kilometer in flight and it was estimated through expert judgement; it covers all drone related costs (e.g. energy consumption and maintenance). Parameter $\delta_d$, is the fraction of the drone operating costs during ascent (i.e. more energy is used during ascent), while $\epsilon$ is the fraction of the drone operating costs during descent (i.e. less energy is used during descent). The cost of the personal protective equipment $c_{pe}$ including overall, safety glasses, respiratory mask and gloves arises as both health care professionals must apply it before visiting a patient location. One mask is also provided to the patient. The cost estimate is based on market prices during the COVID-19 pandemic. Disinfecting the vehicle after every tour incurs cost $c_d$ for the disinfectant material. This is commonly performed with specialized disinfectant wet wipes. For the drone, $c_d$ is the cost of disinfectant material used to disinfect the drone after every single patient location visit. The considered drone is routinely cleaned with an alcoholic solution so this can also be performed during a potential contamination situation.

Finally, the associated time estimates are presented, where $t_p$ is the time required for the entire test conducted by the mobile testing team. This includes several steps, such as initial screening, dressing with personal protective equipment and the actual conduct of the test. The estimate is based on practitioner experience and personal on-site observations. The time required to conduct the self-test ($t_{st}$) was estimated through empirical observation. Parameter $t_m$ is the time required to adequately hand over the test tubes for further processing. Disinfection of the minivan requires time $t_m$ and for the drone time $t_d$. Both estimates are based on expert information and were empirically validated. As the considered drone model is water-resistant, a spray disinfectant could also be considered to speed up this process. Loading and unloading the drone with the self-test kit takes time $t_l$. It was estimated through the practical performance of the task. After every battery swap, the drone needs startup time $t_s$ before it can take off again. This is specific to the drone model under consideration. The time for a battery swap is denoted by $t_w$ and it was estimated through the practical performance of the task.

### 3.3. Estimation of distance travelled

Before presenting the distance estimates developed for the aim of this study, we briefly have to clarify the decision concerning travel distance estimation as it differs from other related studies. Reggiani (2013) pointed out the importance of a network view including a multitude of system elements when regarding the resilience of transport systems. Such a view was taken in several existing studies concerning the applicability of drones in transport related disaster response or preparation contexts (Mosterman et al., 2014; Rabta et al., 2018; Wankmüller et al., 2020). However, as we are investigating the use of already existing infrastructure, we do not consider a drone location problem that could be solved using various optimization approaches.

A key element for the developed cost and time functions is the total distance the transportation modes – vehicles and drones – have to travel to service the $n$ different patient locations in one tour. Through empirical evidence we found that with the VBT a vehicle can travel from one patient location ($i$) directly onwards to the next location ($j$) due to the storage capacity in the vehicle as well as the possible on-site human intervention. The drone in the DET, on the other hand, has to return to its base station after every conducted test delivery due to a possible equipment contamination, a necessary battery swap and other reasons. A graphical representation of this idea corresponding to Carlson and Song (2018) is given in Fig. 1.

The estimation of total distance for the VBT can hence be treated as a simple travelling salesman problem. As the number ($n$) of patient locations to be visited per trip is rather low, the classic Miller-Tucker-Zemlin approach can be applied (Miller et al., 1960) where $u_i$ is a dummy variable and $x_{ij}$ a binary variable that denotes whether a trip between two locations was made or not. The problem is to find the shortest directed tour for visiting $n$ patient locations. The basic formulation is as follows:

$$\begin{align*}
\min & \sum_{i=1}^{n} \sum_{j=1}^{n} d_{ij} x_{ij} \\
\text{subject to}, & \\
& x_{ij} \in \{0, 1\} \quad i, j = 1, \ldots, n \\
& u_i \in \mathbb{R} \quad i = 1, \ldots, n \\
& \sum_{i \neq j \neq i} x_{ij} = 1 \quad j = 1, \ldots, n \\
& \sum_{j \neq i \neq j} x_{ij} = 1 \quad i = 1, \ldots, n \\
& u_i - u_j + nx \leq n - 1 \quad 1 \leq i, j \leq n \quad i \neq j \\
& 0 < u_i < n - 1 \quad 1 \leq i \leq n
\end{align*}$$

For the DET the situation is quite different, as the drone has to travel to service the patient location ($i$) directly onwards to the next location ($j$) due to the evidence we found that with the VBT a vehicle can travel from one patient location ($i$) directly onwards to the next location ($j$) due to the storage capacity in the vehicle as well as the possible on-site human intervention. The drone in the DET, on the other hand, has to return to its base station after every conducted test delivery due to a possible equipment contamination, a necessary battery swap and other reasons.

### 3.4. Time and cost functions

As the parameter and the distance estimations were laid out we can now dive into the definition of the time and cost functions for the corresponding testing variants. They result from the VBT and DET processes explained above.

The time functions can be derived from the interpreted process map (Table 2); $t_{tot}$ is the total time it takes VBT to visit all patient locations in one tour and return to the base station (Eq. (9)), while $t_{bud}$ is the total time it takes DET to visit all patient locations in one tour and return to the base station (Eq. (10)).

$$t_{tot} = \sum_{i=1}^{n} \sum_{j=1}^{n} \left( \frac{d_{ij}}{v_a} \right) + (t_p \cdot n) + t_m + t_d$$

$$(9)$$
Correspondingly, the cost functions can be derived as well; \( ac_{\text{tot}} \) is the total cost incurred by VBT visiting all patient locations in one tour and return to the base station (Eq. (11)), while \( bc_{\text{tot}} \) is the total cost incurred by DET visiting all patient locations in one tour and return to the base station (Eq. (12)).

\[
bc_{\text{tot}} = (t_i * l_0 * 4n) + \left( \frac{b}{v_b} * l_0 \right) + \left( t_i * c_i * 2 \right) + \left( \left( t_i + t_m + t_h + t_a + t_s \right) * n \right) + \left( c_0 * n \right)
\]

(12)

### 3.5. Model simulation, assumptions, and validation

To analyze the different testing variants with the above identified time and cost functions we used a mathematical model built in the interpretative programming language ‘R’. The chosen methodology is a well-established approach for generating insights in this regard and a multitude of scientific studies have previously performed similar analyses (e.g. Zavvar Sabegh et al. (2016), Knofius et al. (2019), or Bosch et al. (2018)). In regard to drones, the works by Chowdhury et al. (2017) and Rabta et al. (2018) were also of importance.

The first step for model simulation, hence, was to estimate the respective total sum of travel distance. Therefore, we randomly (uniformly) computed \( n+1 \) different locations in a two-dimensional Euclidean space and applied the above explained distance estimation approaches. The additional location is the assumed base station for either VBT or DET (which is indexed as location 0). The designated base station was chosen randomly (uniformly) from the \( n+1 \) randomly generated locations, because we investigate the use of already installed drone infrastructure that might be located anywhere within the area under regard. This means that the VBT and DET base stations are not necessarily situated in the same location, and neither does either one have to be located in the center of the area. The area under regard is circular and limited in size by the maximum range of the drone. In our case, the maximum range is limited by the battery capacity which lasts for 36 km of flight distance. As the drone has to be able to perform a return flight to and from every point in the two-dimensional area, the maximum diameter is 18 km. This corresponds to an area of roughly 250 km², which is about two times the size of the land area covered by the city (~100,000 inhabitants) where the empirical data gathering for this study was conducted. As a further note on distance estimation, we assume beyond visual line of sight (BVLOS) communication between the

| Table 2 |
| --- |
| Process map with associated time and cost function elements. |

| Vehicle-based Testing | Drone enabled Testing |
| Activity | Time | Cost | Activity | Time | Cost |
| --- | --- | --- | --- | --- | --- |
| Drive to patient | \( (d_{p} * v_{p}) \) | \( (d_{p} * c_{p}) + (d_{p} * v_{p}) * l_{0} \) | Loading | \( t_{l} \) | \( (t_{l} * b_{l}) \) |
| Dressing | \( t_{d} \) | \( (t_{d} + l_{0}) + c_{d} \) | Startup | \( t_{s} \) | \( (t_{s} * b_{s}) \) |
| Preparation and testing | \( t_{p} \) | \( (t_{p} + l_{0}) + c_{p} \) | Vertical ascent | \( (h/v_{h}) \) | \( (h/v_{h}) + b_{h} + (h * c_{h}) \) |
| Undressing | \( t_{u} \) | \( (t_{u} + l_{0}) \) | Horizontal flight to patient | \( (d/v_{d}) \) | \( (d/v_{d}) + (d/v_{d}) * b_{h} \) |
| Test handover | \( t_{h} \) | \( (t_{h} + l_{0}) \) | Vertical descent | \( (h/v_{h}) \) | \( (h/v_{h}) + b_{h} + (h * c_{h}) \) |
| Drive to next patient/station | \( (d_{p} * v_{p}) \) | \( (d_{p} + c_{p}) + (d_{p} / v_{p}) * l_{0} \) | Unloading | \( t_{l} \) | \( (t_{l} * b_{l}) \) |
| Final disinfection | \( t_{f} \) | \( (t_{f} + l_{0}) + c_{f} \) | Self-test | \( t_{s} \) | \( (t_{s} * b_{s}) \) |

| Table 3 |
| Maneuvering and communication ranges for the considered drone model. |

| Maneuvering/Communication | Max. Distances | (Beyond) visual line of sight |
| --- | --- | --- |
| Max. range video signal (analog) | 1 km | VLOS |
| Max. line of sight operator-drone | 2–3 km | VLOS |
| Max. range video signal (digital) | 20 km | BVLOS |
| Max. range user-controlled | 20 km | BVLOS |
| Max. range battery capacity | 36 km (18 km return flight) | BVLOS |
| Max. range autonomous flight | Limited by battery capacity | BVLOS |
operator and the drone as the maximum flight distance exceeds the visual line of sight (VLOS) of 2–3 km achievable in a flat and open area. In Table 3, the maneuvering and communication ranges of the considered drone model are listed. Here, it becomes evident that the maximum range is limited by battery capacity on a return flight (18 km) as it is shorter than both the maximum range of the video signal in digital mode (20 km) as well as the maximum range of user control (20 km).

For modelling purposes, the total distance estimation process was repeated over 100 iterations (tours). Following Cleophas and Ehmke (2014) we multiplied the distance travelled by the VBT with a correction factor of 1.5 to make it comparable to the route taken by the DET. This is due to the fact that the direct Euclidean distance between two points is usually shorter than the shortest path distance in a real road network. Based on the results from the total distance per tour estimations, we then calculated the corresponding time and cost estimates following the equations as described above.

During the model design, several assumptions were made. For simplicity’s sake, we refrained from simulating acceleration as a function within the overall time and cost functions, as this would have had little effect on model results. For the same reason, flight altitude was assumed to stay constant and no adjustments for potential geographic altitude changes were included. A further necessary model assumption is that all locations within the regarded area can be served by both transport mode alternatives. This, however, limits the circular operating space to a diameter of 18 km, which, in turn, is necessary for the direct comparison. In this regard we also had to make the assumption that such an operating distance for the drone is legally allowed, which currently is often not the case. Furthermore, it is assumed that there are no constraints for the available number of spare batteries for the drone as unlimited battery swap capacity is available, which is reasonable as spare batteries can be recharged while the drone is operating with another set of batteries. The cost of the test kits themselves were not included in the assessment as they are not part of the necessary comparison.

The validity of the model was ensured by designing and cross validating the conceptual design with empirical evidence provided by the involved organizations. This was comprehensively described in previous sections. The numerical validity was tested by comparing the results from the calculated travel and working times with real working conditions of both health care professionals and drone operators as well as with empirical viral test data.

4. Results and discussion

Several health care professionals conducting the tests by VBT were asked about the number of COVID-19 tests they take on a daily basis (i.e. per tour). They reported that the maximum number of tests they took on a given day was 84, but this took place in only one location, namely a residential home for the elderly. This constitutes an extreme case for which drone delivery would not be practical. We therefore regarded the range of the number of patient locations the health care professionals usually visit per tour. According to their personal experiences, this number (n) ranges between a handful of patient locations to up to a maximum of 23 locations per tour. Correspondingly, we decided to estimate travel distances for four different scenarios (n = 5, 10, 15, 20). Consequently, the first results achieved in this comparative analysis are the estimated travel distances per tour by the VBT and the DET. As can be seen in Fig. 2, the vehicle tour routes are remarkably shorter than the necessary tour routes for the drones, as it has to fly all individual routes twice while the VBT can rely on an optimal routing alternative. For the same reasons, the variability of the route length is also greater for DET than for VBT. These downsides are, however, partially offset by higher possible speeds of the drones and their independence from traffic or road infrastructure. The corresponding summary statistics can be found in Appendix b.

Now, as the total travel distances are estimated for VBT and DET, the corresponding time and cost functions can be solved. We therefore regard three different testing variants. First, the VBT with personal testing (VBTₚₚ); this is the process currently applied by the health care organization under regard, where two health care professionals personally visit the patient locations and sample the viral tests. The second (assumed) testing variant is the VBT with self-test kits (VBTₛ). In this case there is only one health care professional (tₚ = 30 €/h) distributing the self-test kits to the patients who then conduct the swap sampling themselves (tₛ) instead of tₚ. With this variant, no special protective equipment is needed (cₛ = 0) as the health care professional can drop off and pick up the tests without direct human contact. The third testing variant is DET, where the self-test kits are distributed and collected with the help of a drone. In Table 4 the results are summarized for the four different scenarios concerning the number of patient locations per tour.

As can be seen, VBTₚₚ is both the fastest and most cost-efficient option among the three variants. In a more detailed perspective relating to the average time it takes the different testing variants to complete a tour (Fig. 3), the times associated with different tasks are depicted. It shows that DET is competitive compared to VBTₚₚ when the number of patient locations to be visited is low (n = 5). As n increases however, DET loses ground compared to VBTₚₚ; and in the n = 20 scenario it is even approximately 2 h slower than the VBTₚₚ. This is mostly due to extra handling, start-up, and disinfection tasks that have to be performed every time the drone returns from a patient location. Additionally, the larger distances the drone has to travel add further transport time. The aim of the proposed concept in this study, however, is to use existing drones as a back-up transport system for emergency cases, and not to create a new and more efficient system. Hence, it can be said that drones remain a viable alternative to vehicle-based test distribution approaches in all scenarios when regarding the time it takes to distribute the tests.

When regarding the associated costs, DET becomes a highly competitive alternative as compared to the other two variants (Fig. 4). Again, VBTₚₚ remains the cheapest option, but the difference to the drone distribution is comparatively low and can mostly be assigned to the labor cost component. The VBTₛ variant in this regard, however, loses by a great margin, mostly due to the high costs here associated with ‘Hygiene’. Most of this stems from the cost for the personal protective equipment the health care professionals have to put on at every patient location. Due to a related surge in the market price during the COVID-19 pandemic, personal testing became a costly variant compared to contactless alternatives.

Achieved results were validated by comparison to real working conditions of both health care professionals and drone operators. In our case, the corresponding collective bargaining agreement states that a regular working day should comprise 8 h, but the common working shift for a health care professional conducting the COVID-19 tests was 12 h. All the testing variants and scenarios fit into this time frame and leave

![Fig. 2. Histogram of total distance travelled of VBT and DET for different numbers of patient locations (n).](image)
Not only does the DET perform comparatively well, but furthermore it provides a way to distribute tests (and other goods) in a contactless way independent of traffic, road infrastructure, or geographic peculiarities. It can further serve to support, and not substitute existing VBT approaches. This can increase the overall number of tests that could be conducted in a given area.

5. Feasibility study

After analyzing the performance of the proposed DET, we empirically explored the technological and practical feasibility of this concept (RQ2). We therefore conducted a field test where we retrofitted a drone originally designed for other purposes to now transport goods (i.e. COVID-19 self-test kits). Three possible approaches were identified, the first being a makeshift construction where a delivery box was attached using material that is available in every workshop, such as cable ties and ropes (see Appendix c). This approach was easily implemented and served the purpose well; no impediments to the flight behavior were felt according to the drone pilot. Loading and unloading of an improvised COVID-19 self-test was performed without any complications and high levels of safety (i.e. unintentional loss of the self-test kit) were given during the entire flight and delivery process. The second approach considered, involved the use of specialized transport boxes that can be attached to the drone via preinstalled attachment rails. As drones are frequently investigated for parcel delivery and other small transport operations (Perboli and Rosano, 2019) such equipment might become increasingly common. This alternative is preferable to makeshift constructions and could eventually be prepared in advance for potential use. The third alternative was pointed out to the authors by the drone manufacturer, and it makes use of a remote-controlled drop-off mechanism. This solution allows the delivery of goods to patients where infrastructural barriers prevent safe drone landing. Instead, the drone takes a hovering position and drops the payload following a signal by the drone operator. This mechanism was initially custom-made for a physician located in an alpine region where he uses such a drone to deliver medical supplies to remote hamlets and alpine farms. This model with its unique drop-off mechanism is already in practical use and could therefore be easily adopted to the use of COVID-19 self-test delivery. However, for the scenario under regard in this study, this is not an option as it would require reliable point-of-care tests as tests cannot be picked up again. That said, if possible, dropping off testing kits would further speed up the delivery process, reduce safety concerns related to drone landings, and prevent a potential contamination of the drone.

As proven in the field trials, the retrofitting of a drone for the purpose of COVID-19 self-test delivery is doable from a purely technological perspective. Nonetheless, one could argue that despite technical readiness, the entire process is vulnerable to patient-related manipulations when conducting the test without professionals on-site. In order to

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**Table 4**

Summary statistics of cost and time estimates for three different testing variants with \( n \) different patient locations.

|         | \( n = 5 \) | \( n = 10 \) | \( n = 15 \) | \( n = 20 \) |
|---------|-------------|-------------|-------------|-------------|
|         | Time Total  | Cost Total  | Time Total  | Cost Total  |
| VBT     |             |             |             |             |
| Min     | 2.6 h       | 327.7 €     | 5.0 h       | 634.8 €     |
| Mean    | 3.4 h       | 386.4 €     | 5.4 h       | 668.1 €     |
| Max     | 3.8 h       | 419.7 €     | 5.7 h       | 693.2 €     |
| StdDev  | 0.19 h      | 14.81 €     | 0.17 h      | 13.32 €     |
| VBTc    |             |             |             |             |
| Min     | 1.8 h       | 69.0 €      | 3.3 h       | 125.8 €     |
| Mean    | 2.6 h       | 104.8 €     | 3.7 h       | 146.0 €     |
| Max     | 3.0 h       | 125.1 €     | 4.1 h       | 161.4 €     |
| StdDev  | 0.19 h      | 9.03 €      | 0.17 h      | 8.12 €      |
| DET     |             |             |             |             |
| Min     | 2.2 h       | 92.9 €      | 4.7 h       | 205.9 €     |
| Mean    | 2.9 h       | 130.2 €     | 5.7 h       | 255.7 €     |
| Max     | 3.5 h       | 161.9 €     | 6.5 h       | 298.8 €     |
| StdDev  | 0.26 h      | 13.35 €     | 0.39 h      | 20.28 €     |

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**Fig. 3.** Total time it takes to finish a tour on average for the different testing variants with increasing \( n \).

**Fig. 4.** Total average cost of a tour for the different testing variants with increasing \( n \).
tackle this issue, camera equipment already installed on the drone can be used, where an ID card in combination with a facial image could easily be identified through the transmitted image. Alternatively, Li et al. (2017) have proposed the (semi-)autonomous delivery of goods to the customer supported by a digital application. In this case, the verification of the customer identity is done via QR-code scanning previously transmitted through a mobile application. Concerning the communication with the patient, the authors found that the application of remote-controlled loudspeakers and drone-lighting can be helpful technological support solutions.

6. Policy implications

Among several government measures taken during the COVID-19 pandemic, social distancing, contact tracing, quarantine, and extensive testing have been the most prominent. Concerning testing, Cohen and Kupferschmidt (2020) reported that national testing tactics mostly revolved around mobile testing and stationary testing, where people are tested on a drive through strategy. Padula (2020) however stressed that in some areas the distribution of COVID-19 is a challenging task, especially in less densely populated or mountainous regions. In this regard, the establishment of a backup transportation system using retrofitted drones, as envisioned in this study, is a promising solution. Associated benefits are that no new infrastructure has to be sourced and investments are limited to preparatory measures and policy creation. This can greatly enhance the resilience of the related transport systems and the health care environment which, according to Hsieh (2020), already reached its limits on some occasions. To establish such a back-up system several steps have to be taken, however (relating to RQ3).

The importance of designing sound transport policies to enhance system resilience has already been studied in the context of other scenarios. Cox et al. (2011) for example, evaluated transport system resilience and the role of corresponding policies towards terrorist acts. Among other mitigation strategies they propose moving to alternative transportation modes, the establishment of back-up systems, and general technological shifts. In the study at hand, similar policy strategies are proposed even though in a very different setting; namely during (COVID-19) pandemic response. Manca and Brambilla (2011) found in a different transportation related system analysis that crucial success factors in emergency response rely on proper emergency preparedness activities that include the definition of responsibility areas, roles and interventions to speed up decision-making and information-sharing. Key issues are the distributed evidence of available resources, know-how, and management activities. In addition, Markolf et al. (2019) emphasize the importance of modular, connective, and compatible technical structures enhanced through the cooperation with internal and external entities. Therefore, we recommend fostering corresponding public-public and public-private partnerships in pre- and post-disaster times. Management activities have to be coordinated, and a certain degree of system proficiency must be established as well. Scenario planning and the conduct of related training activities are recommendable.

In the case of drone usage, a significant enabling role lies in the underlying legal framework, especially when applied in the medical domain (Konert et al., 2019). Several practitioners also pointed out legal concerns to the authors during their empirical investigations when scrutinizing the proposed analysis. In that regard, the International Air Transport Association (IATA, 2019) identified the clear need to develop the relevant standards, partnerships, and legal frameworks for the safe integration of cargo drones into the airspace. The European Union Aviation Safety Agency (EUASA, 2020) also takes measures in that direction, but a lot of white space remains. It hence can be regarded as a policy priority to establish unified and conclusive rules and norms concerning the application of drones during disaster situations. This should be developed in cooperation with involved organizations, also bearing in mind unconventional approaches for drone deployments, as proposed in our study.

Several involved experts embraced the idea of viral test distribution via drones, and one leading health care professional claimed that such a transport approach can significantly lower the risk of further spreading of the disease in the testing process itself. This might become particularly interesting in the case of highly infectious diseases where the risk of self-infection of the testing team is high. Additionally, he pointed out that drone enabled distribution can free up desperately needed resources, in this case health care personnel, for their use in other relevant tasks and hence take strain off the health system. A drone enabled back-up system could be a valuable asset in any disaster related government contingency plan.

A more practical policy recommendation concerning the actual establishment of the envisioned drone enabled back-up transport system became apparent to the authors when regarding the prominence of volunteering in Austria, especially during the COVID-19 response. According to Spritzer et al. (2019) 46% of the Austrian population, or around 3.3 million people, participate in voluntary activities. Around 7% percent of the total population are in a formal voluntary engagement in the field of disaster relief or rescue operations, and another 5% formally participate in social or health organizations. The authors hence suggest embedding private drone operators and professional drone pilots into the formal service structure of involved organizations, such as the Red Cross, voluntary fire fighters, or mountain rescue services to enable fast deployment of the backup transportation system when the need arises. By doing so, several policy related challenges could be alleviated, as a dense legal framework, organizational structure, and public know-how are already established in that regard.

Further potential guidelines for the implementation of the envisioned drone enabled backup transport system revolve around the practical utilization of the drones in a particular area. In this study, a comparison between VBT and DET was presented as a first investigation. While this provides valuable initial orientation, once a test or distribution strategy might be rolled out it will also be important to find ways to efficiently match delivery destinations and available drone capacities in a given area. We recommend to rely on mathematical optimization approaches as presented for example by Wankmüller et al. (2020). The task is to optimally allocate the DET from multiple predefined locations to the delivery destinations in a way that minimizes flight time or cost. Through such an approach a transparent decision-making process is provided to policymakers.

7. Conclusion

In this study we were able to show how a back-up transportation system based on existing drone infrastructure can play a vital role in response to the COVID-19 pandemic and comparable situations. Based on empirical evidence we found several scenarios where time or cost benefits can be harnessed, and in any case, drones provide a contact free, flexible, and fast alternative to classic transportation modes. By relying on existing drone infrastructure, we developed a system where no or little investments have to be made for a powerful disaster response tool. However, we also found out that transport policy in the post COVID-19 world will have to look different in order to permit such innovative delivery options. Especially the establishment of a proper and targeted legal framework remains a key challenge. The establishment of public-public and public-private partnerships will also have to be carried on by policymakers in the future. In that regard, this study may serve as a guideline and decision-making foundation for people in charge of fostering further steps towards the anticipated backup drone delivery.
system. From an academic point of view, we were able to take a novel look at the time and cost efficiency of drones as no such study has been conducted before. Additionally, studies also focusing on transport policy recommendations concerning the use of drones are sparse and this study contributes to the creation of a corresponding academic discourse.

Nevertheless, several limitations of this study remain; first, the empirical evidence is based on one region and model results as well as policy recommendations might look different in other environments. Second, the developed cost and time model is limited in certain directions. Fixed costs, such as purchase costs, were neglected, as in this study the focus lies on designing a response policy entirely based on existing infrastructure. In the time and cost estimations for the drone, the additional weight for self-test kits was not included. The reason is that we work with retrofitted drones where the original equipment will be replaced with a container and loaded with the kits. Estimating the weight difference for the drone is hence individual to every case but could easily be included into the existing model when needed. Third, the legal feasibility of the proposed approach was assumed as a given, knowing that the real situation is quite the opposite. In particular, our assumption of operating a drone beyond visual line of sight is in practice restricted by legal regulations. That means, that you are in general only allowed to fly a drone within the line of sight from a legal perspective, which would be approximately 2–3 km depending on geographic and weather conditions. This distance is however exceeded during this study for the reason that corresponding legal changes are on their way and some have already been released on a national or international level. The Austrian air navigation service provider, for instance, grants certificates for specific drone flights where line of sight communication is no more mandatory. Future research could aim at extending the present study in regard to aforementioned limitations. Third, the legal feasibility of the proposed approach was assumed as a given, knowing that the real situation is quite the opposite. In particular, our assumption of operating a drone beyond visual line of sight is in practice restricted by legal regulations. That means, that you are in general only allowed to fly a drone within the line of sight from a legal perspective, which would be approximately 2–3 km depending on geographic and weather conditions. This distance is however exceeded during this study for the reason that corresponding legal changes are on their way and some have already been released on a national or international level. The Austrian air navigation service provider, for instance, grants certificates for specific drone flights where line of sight communication is no more mandatory. Future research could aim at extending the present study in regard to aforementioned limitations. Additionally, we propose to conduct comparable studies in different locations and circumstances. From a methodological point of view, it would be interesting to take a more holistic approach to the idea of using existing drone infrastructure as a back-up transportation system. Therefore, studies regarding multiple drone locations in a region, possibly through geospatial modelling or complex route optimization problems with fixed drone locations, are encouraged.

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Notes

The authors want to state that no patient related data was used at any point of this study, and no direct patient contact was established.

CRediT authorship contribution statement

Maximilian Kunovjanek: Conceptualization, Data curation, Formal analysis, Empirical, Investigation, Methodology, Programming, Validation, Visualization, Article, Writing – review & editing. Christian Wankmüller: Conceptualization, Data curation, Formal analysis, Empirical, Investigation, Methodology, Validation, Article, Writing – review & editing.

Declaration of competing interest

None.

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Appendix

Appendix A. Personal protective equipment dressing process at the patient location for vehicle-based testing (Source: the authors)
Appendix B. Summary statistics of total distance travelled of VBT and DET for different numbers of patient locations (n)

| n   | VBT  | DET  | VBT  | DET  | VBT  | DET  | VBT  | DET  |
|-----|------|------|------|------|------|------|------|------|
|     | Min  | 24.6 km | 26.8 km | 51.7 km | 84.4 km | 67.0 km | 165.8 km | 72.1 km | 221.0 km |
|     | Median | 55.5 km | 82.8 km | 69.7 km | 163.3 km | 80.9 km | 241.2 km | 90.8 km | 332.5 km |
|     | Mean  | 55.2 km | 84.1 km | 69.1 km | 161.0 km | 81.1 km | 246.9 km | 91.2 km | 332.6 km |
|     | Max   | 72.5 km | 132.9 km | 82.2 km | 227.4 km | 94.0 km | 372.4 km | 105.4 km | 447.2 km |
|     | StdDev | 7.71 km | 20.54 km | 6.94 km | 31.21 km | 5.90 km | 46.42 km | 5.84 km | 50.92 km |

Appendix C. Retrofitted drone for COVID-19 test distribution with makeshift construction (Source: the authors)

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