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The impact of COVID-19 measures on COPD management and patients: A simulation-based decision support tool

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Abstract

Objectives: To develop a computer-based decision support tool (DST) for key decision-makers to safely explore the impact on COPD care of service changes driven by restrictions to prevent the spread of COVID-19.

Design: The DST is powered by discrete event simulation (DES) which captures the entire patient pathway. To predict the number of COPD admissions under different scenario settings, a regression model was developed and embedded into the tool. The tool can generate a wide range of patient- and service-related outputs. Thus, the likely impact of possible changes (e.g., COVID-19 restrictions and pandemic scenarios) on COPD patients and care can be estimated.

Setting: COPD services (including outpatient and inpatient departments) at a major provider in central London.

Results: Four different scenarios (reflecting the UK government`s Plan A, Plan B and Plan C in addition to a benchmark scenario) were run for 1 year. 856, 616, and 484 face-to-face appointments (amongst 1226 clinic visits) are expected in Plan A, B, and C, respectively. Clinic visit quality in Plan A is found to be marginally better than Plan B and C. Under coronavirus restrictions, lung function tests decreased more than 80% in Plan C as compared to Plan A. Fewer COPD exacerbation related admissions were seen (284.1 Plan C vs 395.1 in the benchmark) associated with stricter restrictions. Although the results indicate that fewer QALYs (in terms of COPD management) would be lost during more severe restrictions, the wider impact on physical and mental health must also be established.

Conclusions: This DST will enable COPD services to examine how the latest developments in care delivery and management might impact their service during and beyond the COVID-19 pandemic, and in the event of future pandemics.

Keywords: remote monitoring, COVID-19, COPD, simulation, decision making

Strengths and limitations of this study

- We provide the first model to support key decision-makers to investigate the impact of COVID-19 measures on COPD management
- The decision support tool can be employed by other COPD services in the UK with minor changes.
- Future works is needed to assess the impact of COVID-19 and the effects of restrictions and shielding on patients` wider physical and mental health.

1. Introduction

Due to restrictions to prevent the spread of COVID-19, the care and treatment for Chronic Obstructive Pulmonary Disease (COPD) patients significantly changed from the start of the pandemic. COPD services witnessed disruption, change and uncertainty and that looks set to continue. Clinic appointments and some COPD services moved to remote care where possible. Some services (e.g., lung function testing) which can only be carried out on-site were severely disrupted.

COPD exacerbations, a main driver of hospital admissions, are often caused by respiratory viral infections. A significant reduction was reported in the rate of viral infections in exacerbation related admissions during the pandemic as compared to the pre-pandemic time.[1-3] Furthermore, a 50% reduction in hospital admissions for COPD exacerbations was observed during the COVID-19 pandemic period according to a recent meta-analysis covering studies from 10 countries including the UK, Spain, China, Singapore.[4] The rate in the studies ranged from 27% to 88% and 10 of 13 studies reported a ≥50% reduction in admissions.

Similarly, Clinical Commissioning Groups (CCGs) in England experienced a significant decrease (i.e., about 45%) in emergency admissions for COPD, from 246.7 per 100,000 population in the financial year of 2019/20 to 133.5 in 2020/21.[5] The main reasons for these reductions are likely to be increased use of hygiene, face coverings and shielding at home, change in patient behaviour (e.g., healthier lifestyle, adherence to medicine), displacement of the primary admission diagnoses by COVID-19, and reduction in air pollution, such as nitrogen dioxide (NO2).[4-7]

Despite mass vaccination efforts in the UK, the number of COVID-19 cases continued to be high. This was mainly due to the emergence of new highly infectious variants and easing the restrictions. As of January 2022, the country recorded the highest cases since the outbreak started, i.e., about 200,000 cases per day. Therefore, any further increase in coronavirus restrictions may lead to a further negative impact on COPD management.

There is the need to understand the impact of COVID restrictions on COPD services, and modelling this provides a way to predict demand and consequences. We developed a computer-based decision support tool (DST) to explore the impact of service changes driven by the COVID-19 pandemic restrictions through a simulation model depicting a COPD service in a virtual environment. The DST tool is powered by discrete event simulation (DES), an approach widely used in the healthcare context. Examples of DES studies include improving financial and clinical outcomes[8,9], redesigning of patient pathways[10,11], increasing operational efficiency[12-14] and better resources management in of COVID-19 services.[15-17] DES is a highly versatile methodology, which can be adapted to different diseases and healthcare services in the safety of a computer-based environment. Users can test a wide range of "what-if" scenarios to increase performance, effectiveness, as well as predict, with a high degree of confidence, the likely outcomes of policies and decisions on healthcare services both now and in the future.

2. Methods

Study Description

The DST is powered by DES method which is widely accepted by healthcare professionals and the National Health Service (NHS) in the UK.[18] The flow diagram in **Error! Reference source not found.** shows the high-level structure of the DST, which includes the COPD patient pathway and the COVID-19 component. The tool integrates the DES model representing COPD patient pathways with the COVID-19 component, which predicts the number of admissions to the pathways. The COPD DES model in Yakutcan et al. (2020)[19] was updated for the context of the pandemic with admission model for exacerbations and embedded in the simulation.

The COPD patient pathway was conceptualised with Royal Free Hospital (RFH) and Central and North West London (CNWL) NHS Foundation Trust. The pathway is broadly described in the modelling study for improving COPD management.[19] The pathway is comprehensive and captures the important parts of the care processes; outpatient clinics (COPD, general, non-invasive ventilation, Alpha-1, Advanced), outpatient services (lung function testing, pulmonary rehabilitation (PR), physiotherapy), emergency and inpatient departments. The pathway and simulation model are described in detail in Yakutcan et al. (2020)[19].

COVID-19 Measures and COPD Management

By the end of March 2020, the service delivery method switched to remote care (where possible) in line with national restrictions regarding COVID-19 in the UK. A hybrid method of service delivery was adapted by COPD services at RFH, a combination of face to face (F2F) and remote consultations. Appointments could be F2F in a clinic room or remote via telephone or video call.

LF testing can only be carried out on site with testing rooms ventilated after each test to reduce the transmission of the virus. Therefore, LF testing capacity was immensely reduced due to COVID-19 rules. Consequently, consultants referred only the most essential COPD patients to LF testing. On a positive note, the hospital`s records showed 40% reduction in exacerbation related COPD admissions during the pandemic compared to the previous year.

The Decision Support Tool

The tool predicts the likely impact of possible changes to care delivery processes on the patients and the COPD service over a period of time. The DES model represents the movement of COPD patients in the service and predicts the number of admissions (considering historical hospital data, restriction and air pollution data), service and patient outputs under different restrictions and pandemic scenarios.

Service capacity, appointment type, referral rates, and the number of COPD exacerbation related admission inputs are subjected to rigorous evaluation under various restriction levels.

For example, under light restrictions, referral rates to LF testing and its capacity and the number of available F2F appointments in the clinics is higher than under stringent restriction.

The tool can generate a wide range of patient- and service-related outputs including quality-adjusted life year (QALY), number of hospitalisations and deaths, number of visits by appointment type (remote, face to face), service quality, and the number of patients waiting for services.

Model Parameters and Data Sources

The tool integrates a DES model representing COPD pathways with a COVID-19 component predicting the number of admissions. It includes a total of 70 input parameters, which were derived and extracted from several sources including national Hospital Episodes Statistics (HES) dataset[20], existing literature, online datasets, and local data and clinicians from RFH/CNWL. The input parameters cover aspects such as demand, mix of resources, treatment times, referral rates, appointment type (remote or face-to-face) as well as stringency index, air quality, and COVID-19 outcomes. A full list of the input parameters is provided in the supplementary file Table S1. Note that all inputs can be customised by the end-users to allow modelling in other services.

The input parameters cover the situation before and during the COVID-19 pandemic with regard to parameters such as referral rate to LF testing and resources. Several statistical distributions were considered in the model to represent accurately the parameters subject to uncertainty, for example. length of stay, QALY, referrals, and death rates. In addition, a survey about the quality of F2F versus remote appointments was conducted amongst healthcare professionals involved in COPD care in the UK. The participants were asked to compare their experience in remote and face-to-face appointments on a scale of worse, same, or better. The survey results and experts` opinion were used as an input for appointment quality by as a means of statistical distributions.

In line with published literature[21,22], QALYs are considered to be driven by the type of service/treatment, severe exacerbation, and the type of appointment (remote or F2F). Patient related outcomes were extracted based on the studies in the literature for the following outcomes: PR[21-23], LF testing[24], physiotherapy[25,26] exacerbation[27], and treatment[28].

Statistical Analysis and Admission Model

COVID-19 outcomes, air quality, government response, and air temperature were the variables of interest with regard to the number of exacerbation related COPD admissions as their partial associations are mentioned in the literature.[1-4] A remarkable reduction in exacerbation is experienced in many countries, which may be related to various factors, e.g., shielding, patient behaviour, and air pollution. Therefore, the relationship between the selected factors and COPD admissions are analysed and an admission model is constituted. The structure of the admission model was explored using data over a period of two years including a year before and a year during the pandemic, that is from 1st March 2019 to 28th February 2021.

The data were obtained from various data sources: (i) COPD admissions from RFH, (ii) COVID-19 outcomes, i.e. weekly cases and weekly deaths, were obtained from Camden Council`s website (available at https://opendata.camden.gov.uk/stories/s/su29-zfnp), (iii) Stringency index (SI) and new COVID-19 admissions were taken from the dataset by the Oxford Coronavirus Government Response Tracker (OxCGRT) (available at https://github.com/OxCGRT/covid-policy-tracker/tree/master/data). The SI measured 0-100 (higher score indicate more restriction). Lastly, air quality data was obtained from the observation sites in Camden where RFH`s patients reside (https://www.londonair.org.uk/london/asp/datadownload.asp). The air quality level is captured through the level of the different pollutants present in the air. These are: nitrogen dioxide (NO2), particulate matter (PM2.5 and PM10), ozone (O3), nitric oxide (NO), oxides of nitrogen (NOX), sulphur dioxide (SO2).

The structure of the relationship between exacerbation related COPD admissions and the variables mentioned above were explored on a weekly, bi-weekly, and monthly basis. Lag effects of the conditions (e.g., SI level, number of COVID-19 cases), i.e., 7 and 14 days, were also considered as the impact of these variables on the exacerbations might emerge after a period of time. Based on weekly admissions, a strong negative correlation between the number of COPD admissions and SI (-0.80) is observed. The association between COVID-19 outcomes (ranged -0.54 and -0.34) and exacerbation was weak. On the other hand, higher air pollutants were found to be associated with more admission (moderate estimate up 0.61). The correlation estimates for a weekly basis are given in Table 1.

Table 1 Correlation estimates between exacerbations related COPD admissions and the variables of interest

Variables (weekly)	N	Correlation Estimate	P-Value
COPD admission (a week ago)	100	0.91	<.0001
COPD admission (two weeks ago)	100	0.81	<.0001
Stringency index (SI)	100	-0.80	<.0001
COVID-19 case	100	-0.43	<.0001
COVID-19 admission	100	-0.54	<.0001
COVID-19 death	100	-0.47	<.0001
Temperature	100	-0.07	0.52
Nitric oxide (NO)*	100	0.60	<.0001
Nitrogen dioxide (NO2)*	100	0.58	<.0001
Oxides of nitrogen (NOX)*	100	0.61	<.0001
Sulphur dioxide (SO2)#	100	0.09	0.403
Ozone (O3)#	100	-0.21	0.036
PM10#	100	0.13	0.205
PM2.5#	100	0.16	0.145

Note: Air quality monitoring stations in Camden: *Holborn, #Bloomsbury

Following the correlation analysis, a multiple regression was carried out to estimate the number of COPD admissions. The structure of the relationship is given below in Eq.1 (adjusted R square of 0.83 and p-values of coefficients below <.0001).

$$\mathbf{COPD\ Admission}\ (\mathbf{t}) = 1.578 + 0.689 * COPD\ admission(t-1) + 0.014 * Nitrogen\ dioxide\ (t) - 0.01 * Stringency\ index\ (t)$$

(Eq.1)

The equation suggests that the total number of exacerbation related COPD admissions at the current week is dependent on previous week`s admissions, plus a multiplicative factor of the average of NO2 level at present week, less a fraction of the SI at the current week (on average). Weekly basis estimates were chosen for the regression model as their statistical outputs were superior to bi-weekly and monthly basis. Some air quality parameters including temperature were insignificant in prediction exacerbations. The regression model above is embedded in the simulation model as inputs regarding the number of COPD admissions, taking in account the different scenario settings.

Patient and public involvement

There was no patient or public involvement in the conduct of the study.

3. Results

Experimentation

The COPD simulation model was statistically validated for the year 2020/21, comparing the results generated by the DST with data observed at RFH. The outputs were within 5% on either side of real data, which confirms the validity of the model, endorsing use in practice.

The simulation period was set and run for 1 year (01st January 2022 – 31st December 2022). Four different scenarios were selected considering the UK government`s plan for COVID-19 related restrictions. Appointment types for outpatient clinics and services, referral and capacity rates for LF testing are adjusted to reflect the restriction level on a weekly/monthly basis during the simulation period. Table 2 shows the summary of the parameters in each scenario with approximate values. Note that the parameters in the scenarios are varied for each week/month.

The details of the scenario settings are available in the supplementary file (see Table S1 and S2).

Benchmark scenario simulates an environment, where there are no restrictions and services run as usual (pre-pandemic), i.e., the year 2019. This is a scenario for comparison and to better understand the impact of COVID-19 on COPD services and patient outcomes. *Scenario 1* investigates mild restrictions in line with the UK government`s Plan A. *Scenario 2* includes stricter restrictions, e.g., face masks, work from home, which is the government`s Plan B. *Scenario 3* considers the possible situation where tougher restrictions could be imposed, under Plan C, involving, for example, closure of non-essentials businesses.

Table 2 Some of the parameters in the scenarios

	Benchmark Scenario	**Scenario 1 (Plan A)**	**Scenario 2 (Plan B)**	**Scenario 3 (Plan C)**
Stringency Index (SI)	0	Between 20-25	Between 20-40	Between 20-60
Appointment Type (on average)	F2F: 100% Remote: 0%	F2F: 70% Remote: 30%	F2F: 50% Remote: 50%	F2F: 40% Remote: 60%
Referral Rate to LF Testing	Between 40%-45%	Between 15%-20%	Between 8%-12%	Between 2%-4%
PR Programme Type (on average)	F2F: 100% Remote: 0%	F2F: 25% Remote: 75%	F2F: 15% Remote: 85%	F2F: 0% Remote: 100%

The main driver of the scenarios is SI which affects (i) offered appointment type (F2F or remote), (ii) exacerbations via admission model, and (iii) service capacity and referrals. For example, relaxing restrictions during the summer period will lead to more F2F visits, in contrast to more remote clinics in the winter period due to tighter restrictions. The average split between F2F and remote clinics are as follows: 100/0, 70/30, 50/50, 40/60 for the scenarios, respectively. A hybrid blended approach is adopted for the ongoing delivery of the PR programme. PR is usually carried out in groups of 10-15 patients, increasing the risk of COVID-19 transmission, as a result remote PR was initially the preferred option (i.e., home-based).

Referral rates and capacity of LF testing are also included in the scenarios as these are impacted by the COVID-19 restriction plans. For example, due to service disruption, referral rates are reduced from 40%-45% (pre-pandemic) to around 8%-12% under Scenario 2. Note that the scenario parameters can be tailored just like the input parameters by users depending on their settings and projections.

Model Outputs

The model was developed and tested at RFH and four different scenarios were run over a period of 1 year (excluding the warm-up period of six months). The DST can generate various outputs around service and patient outcomes. The service outputs are given for each scenario in Table 3.

Table 3 Service Outcomes

	Benchmark Scenario	**Scenario 1 (Plan A)**	**Scenario 2 (Plan B)**	**Scenario 3 (Plan C)**
Outpatient Clinics Outputs				
No. of Face-to-face Appointments	1226.5	856.1	615.7	484
No. of Remote Appointments	0	370.4	610.8	742.5
The Quality of Clinic Visits				
Worse than a usual appointment	106.2	292.1	412.7	481.1
Same as a usual appointment	744.9	567	451.4	385.4
Better than a usual appointment	205.7	197.7	192.7	190.3
Lung Function Testing Outputs				
No. of Referrals	515.8	195.5	113.0	29.9
No. of Attendance	330.7	134.2	80.0	22.8
No. of Patients in the Waiting List	148.7	47.1	22.9	4.7
No. of Did not Attends	36.4	14.2	10.1	2.4

More face-to-face appointments are expected as restrictions eased in Scenario 1 (856.1) compared to Scenario 2 (615.7) and Scenario 3 (484). The appointment type (F2F or remote) can affect the appointment quality, in the means of engagement between patient and clinician, patient's familiarity with technology, and self-expression. The appointment quality is benchmarked with a usual appointment for being worse, same, or higher, based on clinician perception of quality via our Twitter survey. 567 appointments in Scenario 1, 451.4 in Scenario 2, 385.4 in Scenario 3, went at a quality level that would be expected at a usual appointment (see Table 3). Moreover, the numbers of appointments went worse than a usual appointment are 292.1 in Scenario 1, 412.7 in Scenario 2, 481.1 in Scenario 3. As a result, the figures shows that clinic visit quality in Scenario 1 is marginally better than Scenario 2 and 3.

The other important finding is that the number of LF tests are impacted by the level of restrictions. Around 330 patients out of 516 referrals) of could be tested under the benchmark scenario considering the current backlog. This drops to 134, 80, and 23 of the referred patients under scenarios 1,2, and 3, respectively. The results show that the backlog in the system will take some time to clear even if the restrictions are fully lifted.

In addition, the model generated patient-related outcomes (amongst 1,600 COPD patients) considering the impact of COPD services and exacerbation (see Table 4). The simulation combined with the admission model showed the change in exacerbation related outputs depending on the scenario settings. The lowest values related to COPD exacerbation inpatient outputs (284 admissions and 1707 bed days) were in Scenario 3 where the stricter restrictions were set, whereas the benchmark scenario had the highest values (395 admissions and 2344 bed days) as SI was set to the minimum level. Lastly, the number of deaths in the hospital was quite close under the different scenarios and varied between 25 and 20 deaths.

Table 4 Patient Outcomes

	Benchmark Scenario	Scenario 1 (Plan A)	Scenario 2 (Plan B)	Scenario 3 (Plan C)
Exacerbation related Outputs				
No. of Admissions	395.1	327.8	305.2	284.1
No. of Used Bed Days	2344.4	1972.6	1830.0	1707.2
No. of Deaths	25.4	24.9	23.6	20.5
Change in QALYs				

via LF Testing	2.39	0.84	0.46	0.11
via PR	2.25	2.93	3.03	2.84
via Exacerbation	-22.77	-18.89	-17.59	-16.37
Total Change in QALYs*	**-18.14**	**-15.13**	**-14.10**	**-13.42**

*The total represents COPD management related QALY changes and does not include changes in mental and physical health due to the restrictions.

With regard to the impact of COPD patients' management on QALYs, the results indicate that the positive change in QALYs via LF testing under the benchmark scenario (2.39) is remarkably higher than under the scenarios 1,2, and 3 (i.e., 0.84, 0.46, and 17 and 0.11, respectively) driven by the high number of referrals and attendances. LF testing itself can only improve patient outcomes indirectly, such as by identifying patients needing institution of, or changes in therapy. As such, the availability of up-to-date LF testing results will enable clinicians to have a better understanding of a patient`s condition and better ability to offer treatment accordingly.[24]

For PR related QALYs, there is a slight variation in the values under different scenarios, all higher than benchmark. This is due to changes in the split in F2F/remote service delivery and attendance/completion rates depending on the restrictions. However, QALYs loss after exacerbations is considerably high under the benchmark (-22.77) as compared to other scenarios. This is due to the relationship between exacerbations, the SI, and other factors such as hygiene, shielding, and air pollution.

Although restrictions and COVID-19 have significantly disrupted service delivery, the reductions in exacerbations and exacerbation related deaths are favourable outcomes for COPD patients. Therefore, the results show that fewer QALYs would be lost (in terms of the course of COPD and disease management) during more severe restriction periods, i.e., -13.42 for Plan C (Scenario 3), -14.10 for Plan B (Scenario 2), -15.13 for Plan A (Scenario 1), and -18.14 if there are no restrictions (Benchmark scenario). On the other hand, the shielding, stricter restrictions, and uncertain future regarding the pandemic might affect wider COPD patients` psychology (i.e., mental health, anxiety, depression) and physical health. These aspects are not covered in the present study as the model focuses on COPD management related outputs. A more holistic approach integrating the impact of COVID-19 and restrictions on physical and mental health of COPD patients would be necessary to capture patient outcomes more completely.

4. Discussion

This research explores the impact of coronavirus restrictions on COPD patients and services to inform stakeholders' (e.g., policymakers, clinicians, and service managers) decision making. The results of the DST tool demonstrate that although reduction in restrictions increases the number of exacerbations, it opens up the opportunity to refer more patients to LF testing and provide F2F visits, which increases the quality of appointments.

The total change in patients` QALY after a year in terms of COPD related incidences (service and patient outcomes) were less under the scenarios where restrictions are tighter. COPD exacerbations, which immensely affect patients QALY and may lead to readmissions or death, are the main drivers of these outputs. The study provided a snapshot of the service and does not imply that restrictions and shielding are beneficial for COPD patients in a holistic sense, despite the profound reduction in exacerbations and hospitalisations. Note that the study focuses on COPD related outputs and has not considered other factors, which may impact QALY such as the impact of the pandemic and restrictions on mental and physical health and the possibility of co-infection with COVID-19.

During restrictions, hospitals generally offered remote services by telephone or availability of digital technology. However, key services like LF testing needs to be conducted on-site, hence this particular service was either discontinued or immensely reduced. Looser restrictions lead to higher capacity in the service and a reduction in waiting times for LF testing. The results show that the backlog in this service will take some time to clear even once COVID-19 related restrictions are fully lifted.

Our survey amongst UK clinicians involved in COPD care questions the appointment quality in remote clinics. The survey pointed out that about 70% of remote clinics appointments had a quality worse than the usual F2F appointment (Only 17% had a better quality than the usual F2F appointment). Clinicians noted that remote visits may be better for some and worse for others. In addition, regarding the comparison between F2F and remote services, a study showed that home-based PR increase QALYs at a similar level compared to hospital-based treatment.[21]

Our analysis showed a strong negative correlation between the number of COPD admissions and SI (-0.80). This is because the COVID-19 preventative measures led to less exposure to bacteria, viruses, and air pollution. In addition, less SI was found to be associated with higher NO2 in the air, where the correlation analysis showed (-0.4). However, against this positive effect of restrictions, it is important to note that restrictions and shielding may cause anxiety and depression affecting mental health adversely.

COPD services have faced immense challenges through the COVID pandemic and continue to do so. Recovering services to pre-pandemic capacity is a key priority if we are to deliver on the respiratory aspects of the NHS Long Term Plan. Services are changing rapidly, as the pandemic evolves, and some aspects of care introduced during the pandemic will likely be retained, for example greater opportunities for remote care where this does not affect quality. Although, COVID-19 is likely to become endemic, the tool will still be useful in the case of future waves or pandemics or when testing the impact of change in delivery methods (e.g., remote, F2F, hybrid, virtual reality, and metaverse).[29-30]

This study has some limitations and assumptions. Due to data unavailability, the following was excluded in the study: COPD patients` deaths due to COVID-19, risk of infection and the impact of COVID-19 (e.g., reduction in QALY, impact of long COVID, and disability).

Furthermore, the physical and psychological impact of shielding and restrictions on COPD patients and their experience in remote clinics are not considered.

These issues can be considered in future work. More specific scenarios with a particular interest in the bottlenecks of the service can be simulated, e.g., increasing the LF testing capacity by offering drive-thru testing. The impact of policies to improve the management of COPD patients can be evaluated via the tool with minor changes. As an example, increasing the use of community services, offering mobile health technologies to monitor patients closely, preventing admissions by detecting exacerbations or readmission early are some possible scenarios.

5. Conclusion

This computer-based DST will enable COPD services to examine how the latest developments in care delivery and management might impact their service during and beyond the COVID-19 pandemic. The model is generic and comprehensive enough to be used by other COPD services in the UK and more widely with only minor adaptations.

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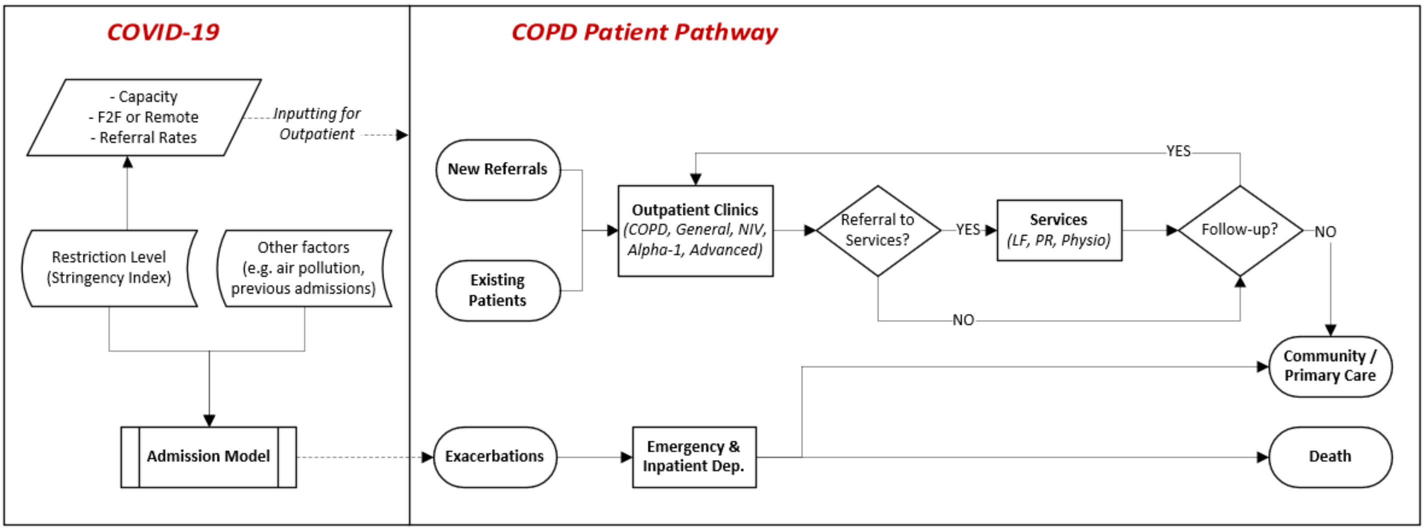

Figure 1 The flow diagram of the decision support tool. *F2F: Face-to-face, LF: Lung function testing, NIV: Non-invasive ventilation, Physio: Physiotherapy, PR: Pulmonary rehabilitation.*

Supplementary File

Table S1 Key Input Parameters of the Model

Input Parameter	Estimate
DEMAND	
Number of COPD exacerbation related arrivals to inpatient department	***Admission Model***
Number of new COPD patients seen in COPD service (weekly)	Uniform (6-9)
Number of existing COPD patients (for Follow-up appointment) seen in the service (weekly)	Uniform (16-22)
Percentage of new patients having a first appointment in each clinic	**COPD:** 32% **General:** 46% **NIV:** 13% **Alpha-1:** 4% **Advanced:** 5%
Percentage of existing patients having a FU Appointment in each clinic	**COPD:** 13% **General:** 66% **NIV:** 11% **Alpha-1:** 8% **Advanced:** 1%
Percentage of patients falling into each gender	**Male:** 52% **Female:** 48%
Percentage of patients falling into each age group	**25-44 years old:** 5% **45-54 years old:** 10% **55-64 years old:** 30% **65-74 years old:** 40% **75-84 years old:** 10% **85+ years old:** 5%
Percentage of patients falling into each disease severity	Mild: 10% Moderate: 40% Severe: 29% Very Severe: 21%
The capacity level for each clinic	**COPD:** Usual **General:** Usual **NIV:** Usual **Alpha-1:** Usual **Advanced:** Usual
OUTPATIENT DEPARTMENT	
Frequency of Clinic days	**COPD:** Once a week **General:** Once a week **NIV:** Once a week **Alpha-1:** Twice a week **Advanced:** Once a month
Attendance rate in each clinic	**COPD:** 75% **General:** 85% **NIV:** 85% **Alpha-1:** 95% **Advanced:** 95%
Appointment types for clinic visits, i.e., face to face or remote	***See Table S2***
Required mix of resources for Reception	**F2F:** A clerk and a desk **Remote:** none
Required mix of resources for Observation	**F2F:** An HCA and a room **Remote:** none
Required mix of resources for COPD and General Clinics	A consultant, an HCA, and a room
Required mix of resources for NIV Clinic	A consultant, an SV practitioner, an HCA, and a room

Required mix of resources for Alpha-1 Clinic	Two consultants, a HCA, a room, a scanner
Required mix of resources for Advanced Clinic	Two consultants, and an MDT, a room
Time spent in Reception per patient by appointment type (per patient)	**F2F:** Uniform (2-5 minutes) **Remote:** 0
Observation time in Observation room per patient by appointment type	**F2F:** Uniform (10-15 minutes) **Remote:** 0
Time spent in COPD Clinic and General Clinic (per patient)	**FA:** Uniform (30-45 minutes) **FU:** 15 minutes
Time spent in NIV Clinic and Alpha-1 Clinic (per patient)	**FA:** Uniform (30-45 minutes) **FU:** 20 minutes
Time spent in Advanced Clinic for First and FU appointments (per patient)	**FA:** 60 minutes **FU:** 20 minutes
Percentage of patients given a FU appointment in each clinic	**COPD:82%** **General:** 100% **NIV:** 80% **Alpha-1:** 95% **Advanced:** 45%
Waiting time for the next FU appointment (i.e., when the patient will come back)	**COPD:** 6 months **General:** 6 months **NIV:** 6 months **Alpha-1:** 6 months **Advanced:** 12 months
The quality of a clinic visit as a face to face appointment	**Worse than a usual appointment:** 10% **Same as a usual appointment:** 70% **Better than a usual appointment:** 20%
The quality of a clinic visit as a remote appointment	**Worse than a usual appointment:** 68,8% **Same as a usual appointment:** 14.3% **Better than a usual appointment:** 17.1%
OUTPATIENT SERVICES	
Percentage of patients referred to Physiotherapy and Pulmonary Rehabilitation	**Physiotherapy**: 15% **PR:** 5%
Percentage of patients referred to LF testing	***Benchmark:*** Between 40-45% ***Scenario 1:*** Between 15-20% ***Scenario 2:*** Between: 8-12% ***Scenario 3:*** Between 2-4%
Appointment types for Physiotherapy and Pulmonary Rehabilitation, i.e., face to face (centre-based) or remote (home-based)	***Benchmark:*** 100% F2F ***Scenario 1:*** 25% F2F, 75% Remote ***Scenario 2:*** 15% F2F, 85% Remote ***Scenario 3:*** 0% F2F, 100% Remote
Appointment types for LF testing, i.e., face to face or remote	100% Face to Face, 0% Remote
The capacity level in Physiotherapy and Pulmonary Rehabilitation	**Physiotherapy**: Usual **PR:** Usual
The capacity level in LF Testing	***Benchmark:*** 100% ***Scenario 1:*** 50-60% ***Scenario 2:*** 20-30% ***Scenario 3:*** 5-15%
Attendance rate for each service	**LF Test:** 90% **Physiotherapy**: 80% **PR:** 69%
Completion rate for Pulmonary Rehabilitation	42%
Required mix of resources for LF Test	A nurse and a room
Required mix of resources for Physiotherapy	A physiotherapist and a room
Required mix of resources for Pulmonary Rehabilitation	A physiotherapist, a nurse, a therapist assistant, a gym, and a classroom

Treatment time in each service	**LF Test:** 25 minutes **Physiotherapy**: Uniform (50-60 minutes) **PR:** Uniform (60-90 minutes)
Pre and Post assessment time in Pulmonary Rehabilitation (per patient)	Uniform (40-45 minutes)
Number of Pulmonary Rehabilitation sessions	16 sessions (2 sessions every week)
INPATIENT DEPARTMENT	
Length of stay in inpatient department	Frequency distribution (Average: 6.1 days)
Percentage of discharge method, i.e., Discharged to Community or PC, and Died.	**Community or PC:** 93% **Died:** 7%
PATIENT OUTCOMES	
QALY Gain due to PR	**F2F (Centre-based):** Uniform (0.029 – 0.032) **Remote (Home-based):** Uniform (0.037 – 0.040)
QALY Gain due to LF testing	Uniform (0.037 – 0.040)
QALY Reduction due to exacerbation related admission	Uniform (0.005 – 0.006)

Notes: Unless specified, the input estimates are the same for each scenario or all visit types. COPD: Chronic obstructive pulmonary disease, **FA**: First Attendance, **FU**: Follow-up, **F2F**: Face-to-face, **HCA**: Healthcare assistant, **LF**: Lung Function, **MDT**: Multidisciplinary Team, **NIV**: Non-Invasive Ventilation, **PC**: Primary Care, **PR**: Pulmonary Rehabilitation, **QALY**: Quality-adjusted life year, **SV**: Sleep & Ventilation.

Table S1 The parameter values of the scenarios

	Benchmark Scenario		**Scenario 1 (Plan A)**		**Scenario 2 (Plan B)**		**Scenario 3 (Plan C)**	
Month	**SI**	**Appt. Type (F2F, Remote)**	**SI**	**Appt. Type (F2F, Remote)**	**SI**	**Appt. Type (F2F, Remote)**	**SI**	**Appt. Type (F2F, Remote)**
Jan-22	0	100%, 0%	25	60%, 40%	40	40%, 60%	60	60%, 20%
Feb-22	0	100%, 0%	23	60%, 40%	40	40%, 60%	60	60%, 30%
Mar-22	0	100%, 0%	23	70%, 30%	40	50%, 50%	50	50%, 40%
Apr-22	0	100%, 0%	23	70%, 30%	35	50%, 50%	50	50%, 50%
May-22	0	100%, 0%	23	70%, 30%	35	50%, 50%	40	50%, 60%
Jun-22	0	100%, 0%	23	80%, 20%	35	60%, 40%	40	40%, 50%
Jul-22	0	100%, 0%	23	80%, 20%	23	60%, 40%	23	40%, 40%
Aug-22	0	100%, 0%	20	80%, 20%	20	60%, 40%	20	40%, 40%
Sep-22	0	100%, 0%	23	70%, 30%	23	50%, 50%	23	50%, 30%
Oct-22	0	100%, 0%	23	70%, 30%	35	50%, 50%	40	50%, 30%
Nov-22	0	100%, 0%	23	70%, 30%	40	50%, 50%	50	50%, 40%
Dec-22	0	100%, 0%	25	60%, 40%	40	40%, 60%	60	60%, 50%

Notes: Appt. Type: Appointment type, **F2F:** Face-to-face, **SI:** Stringency Index.

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Assessing the impact of COVID-19 measures on COPD management and patients: A simulation-based decision support tool for COPD services in the UK

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Abstract

Objectives: To develop a computer-based decision support tool (DST) for key decision-makers to safely explore the impact on chronic obstructive pulmonary disease (COPD) care of service changes driven by restrictions to prevent the spread of COVID-19.

Design: The DST is powered by discrete event simulation (DES) which captures the entire patient pathway. To estimate the number of COPD admissions under different scenario settings, a regression model was developed and embedded into the tool. The tool can generate a wide range of patient- and service-related outputs. Thus, the likely impact of possible changes (e.g., COVID-19 restrictions and pandemic scenarios) on COPD patients and care can be estimated.

Setting: COPD services (including outpatient and inpatient departments) at a major provider in central London.

Results: Four different scenarios (reflecting the UK government`s Plan A, Plan B and Plan C in addition to a benchmark scenario) were run for 1 year. 856, 616, and 484 face-to-face appointments (amongst 1226 clinic visits) are expected in Plan A, B, and C, respectively. Clinic visit quality in Plan A is found to be marginally better than Plan B and C. Under coronavirus restrictions, lung function tests decreased more than 80% in Plan C as compared to Plan A. Fewer COPD exacerbation related admissions were seen (284.1 Plan C vs 395.1 in the benchmark) associated with stricter restrictions. Although the results indicate that fewer QALYs (in terms of COPD management) would be lost during more severe restrictions, the wider impact on physical and mental health must also be established.

Conclusions: This DST will enable COPD services to examine how the latest developments in care delivery and management might impact their service during and beyond the COVID-19 pandemic, and in the event of future pandemics.

Keywords: remote monitoring, COVID-19, COPD, simulation, decision making

Strengths and limitations of this study

- A decision support tool (DST) is developed to investigate the impact of COVID-19 measures on COPD management and patients.
- The DST is powered by a discrete-event simulation model representing the entire COPD patient pathway and a regression model to estimate COPD admissions.
- The relationship between COPD admissions and various variables (e.g., COVID-19 outcomes, stringency index, air quality level) was investigated.
- The physical and mental health related issues (caused by the restrictions) are not included due to unavailability of the data.

1. Introduction

Due to restrictions to prevent the spread of COVID-19, the care and treatment for Chronic Obstructive Pulmonary Disease (COPD) patients significantly changed from the start of the pandemic. COPD services witnessed disruption, change and uncertainty and that looks set to continue. Clinic appointments and some COPD services moved to remote care where possible. Some services (e.g., lung function testing) which can only be carried out on-site were severely disrupted.

COPD exacerbations, a main driver of hospital admissions, are often caused by respiratory viral infections. A significant reduction was reported in the rate of viral infections in exacerbation related admissions during the pandemic as compared to the pre-pandemic time.[1–3] Furthermore, a 50% reduction in hospital admissions for COPD exacerbations was observed during the COVID-19 pandemic period according to a recent meta-analysis covering studies from 10 countries including the UK, Spain, China, and Singapore.[4] The rate in the studies ranged from 27% to 88% and 10 of 13 studies reported a ≥50% reduction in admissions.

Similarly, Clinical Commissioning Groups (CCGs) in England experienced a significant decrease (i.e., about 45%) in emergency admissions for COPD, from 246.7 per 100,000 population in the financial year of 2019/20 to 133.5 in 2020/21.[5] These reductions are largely due to the lockdown rules which encompass behavioural measures to limit transmission of COVID-19[6] and reduce the circulation of the viruses causing COPD admissions. Also, the reductions are linked with the increase in the use of hygiene, face coverings and shielding at home, the change in patient behaviour (e.g., healthier lifestyle, adherence to medicine), displacement of the primary admission diagnoses by COVID-19, and reduction in air pollution, such as nitrogen dioxide (NO2).[4–8]

Despite mass vaccination efforts in the UK, the number of COVID-19 cases continued to be high. This was mainly due to the emergence of new highly infectious variants and easing the restrictions. As of January 2022, the country recorded the highest cases since the outbreak started, i.e., about 200,000 cases per day. Therefore, any further increase in coronavirus restrictions may lead to a further negative impact on COPD management.

There is a need to understand the impact of COVID restrictions on COPD services and patients as well as changes in demand and consequences. Therefore, this study aims to explore the impact of changes in COPD care and admissions driven by the COVID-19 pandemic restrictions. Thus, we developed a computer-based decision support tool (DST) through a simulation model depicting a COPD service in a virtual environment. The tool generates various outputs around service and patient outcomes. The patient outcomes focus on COPD management related changes (e.g., quality of life, admissions). As there is no available data, this outcome does not include physical or mental health issues caused by the restrictions.

2. Methods

The DST tool is powered by discrete event simulation (DES), an approach widely used in the healthcare context. DES mimics systems and their operations at discrete-time points, such as time of arrival, treatment time, and waiting time, capturing the individual movement of patients and all the resources consumed during their visit to hospitals (e.g., a consultation room, diagnostic equipment, human resources, costing). The method provides the ability to model complex systems in the safety of a computer simulation environment, capturing reality with all of the uncertainties.

DES helps the decision-making process for managers, key decision-makers, stakeholders, and policymakers. Therefore, it is widely accepted and applied by healthcare professionals in the UK and the National Health Service (NHS) for various purposes.[9] For instance, the approach was used to evaluate COVID-19 scenarios to prevent capacity-related deaths in intensive care[10], to improve the effectiveness of the cataract treatment pathway[11], for economic analysis of the orthopaedic fracture pathway in Glasgow[12], and to understand the behaviour of patients on choosing services for knee operations in Wales[13]. More examples of DES studies include clinical outcomes[14], redesigning patient[15,16], increasing operational efficiency[17–19] and better resource management in COVID-19 services[20,21].

DES is a highly versatile methodology, which can be adapted to different diseases, patient pathways, and healthcare services in the safety of a computer-based environment. Users can test a wide range of "what-if" scenarios to increase performance and effectiveness. Moreover, the likely outcomes of policies and decisions on healthcare services can be estimated (with a high degree of confidence levels) both now and in the future.

Study Description

The flow diagram in The List of Figure Legend/Caption

Figure 1 shows the high-level structure of the DST, which includes the COPD patient pathway and the COVID-19 component. The tool integrates the DES model representing COPD patient pathways with the COVID-19 component, which estimates the number of admissions to the pathways. The COPD DES model in Yakutcan et al. (2020)[22] was updated for the context of the pandemic with an admission model for exacerbations and embedded in the simulation.

The COPD patient pathway was conceptualised with Royal Free Hospital (RFH) and Central and North West London (CNWL) NHS Foundation Trust. The pathway is broadly described in the modelling study for improving COPD management.[22] The pathway is comprehensive and captures the important parts of the care processes; outpatient clinics (COPD, general, non-invasive ventilation, Alpha-1, Advanced), outpatient services (lung function testing, pulmonary rehabilitation (PR), physiotherapy), emergency and inpatient departments. The pathway and simulation model are described in detail in Yakutcan et al. (2020).[22]

COVID-19 Measures and COPD Management

By the end of March 2020, the service delivery method switched to remote care (where possible) in line with national restrictions regarding COVID-19 in the UK. A hybrid method of service delivery was adapted by COPD services at RFH, a combination of face-to-face (F2F) and remote consultations. Appointments could be F2F in a clinic room or remote via telephone or video call.

LF testing can only be carried out on-site with testing rooms ventilated after each test to reduce the transmission of the virus. Therefore, LF testing capacity was immensely reduced due to COVID-19 rules. Consequently, consultants referred only the most essential COPD patients to LF testing. On a positive note, the hospital`s records showed 40% reduction in exacerbation related COPD admissions during the pandemic compared to the previous year.

The Decision Support Tool

The tool projects, statistically validated with a 95% confidence level, the likely impact of possible changes to care delivery processes on the patients and the COPD service over a period of time. The DES model represents the movement of COPD patients in the service and estimates the number of admissions (considering historical hospital data, restrictions, and air pollution data), service and patient outputs under different restrictions and pandemic scenarios. Service capacity, appointment type, referral rates, and the number of COPD exacerbation related admission inputs are subjected to rigorous evaluation under various restriction levels. For example, under light restrictions, referral rates to LF testing and its capacity and the number of available F2F appointments in the clinics is higher than under stringent restriction.

The tool can generate a wide range of patient- and service-related outputs including quality-adjusted life year (QALY), number of hospitalisations and deaths, number of visits by appointment type (remote, face to face), service quality, and the number of patients waiting for services.

Model Parameters and Data Sources

The tool integrates a DES model representing COPD pathways with a COVID-19 component estimating the number of admissions. It includes a total of 70 input parameters, which were derived and extracted from several sources including national Hospital Episodes Statistics (HES) dataset[23], existing literature, online datasets, and local data and clinicians from RFH/CNWL. The input parameters cover aspects such as demand, mix of resources, treatment times, referral rates, appointment type (remote or face-to-face) as well as stringency index, air quality, and COVID-19 outcomes. A full list of the input parameters is provided in the supplementary file Table S1. Note that all inputs can be customised by the end-users to allow modelling in other services.

The input parameters cover the situation before and during the COVID-19 pandemic with regard to parameters such as referral rate to LF testing and resources. Several statistical distributions were considered in the model to represent accurately the parameters subject to uncertainty, for example. length of stay, QALY, referrals, and death rates. In addition, a survey about the quality of F2F versus remote appointments was conducted amongst healthcare professionals involved in COPD care in the UK. The participants were asked to compare their experience in remote and face-to-face appointments on a scale of worse, same, or better. The survey results and experts` opinions were used as input for appointment quality as a means of statistical distributions.

In line with published literature[24,25], QALYs are considered to be driven by the type of service/treatment, severe exacerbation, and the type of appointment (remote or F2F). Patient related outcomes were extracted based on the studies in the literature for the following outcomes: PR[24–26], LF testing[27], physiotherapy[28,29], exacerbation[30], and treatment.[31]

Statistical Analysis and Admission Model

COVID-19 outcomes, air quality, government response, and air temperature were the variables of interest with regard to the number of exacerbation related COPD admissions as their partial associations are mentioned in the literature.[1–4] A remarkable reduction in exacerbation is experienced in many countries, which may be related to various factors, e.g., shielding, patient behaviour, and air pollution. Therefore, the relationship between the selected factors and COPD admissions is analysed and an admission model is constituted. The structure of the admission model was explored using data over a period of two years including a year before and a year during the pandemic, that is from 1st March 2019 to 28th February 2021.

The data were obtained from various data sources: (i) COPD admissions from RFH, (ii) COVID-19 outcomes, i.e. weekly cases and weekly deaths, were obtained from Camden Council`s website[32], (iii) Stringency index (SI) and new COVID-19 admissions were taken from the dataset by the Oxford Coronavirus Government Response Tracker (OxCGRT) (available at https://github.com/OxCGRT/covid-policy-tracker/tree/master/data)[33]. The SI measured 0-100 (higher score indicates more restriction). Lastly, air quality data was obtained from the observation sites in Camden where RFH`s patients reside[34]. The air quality level is captured through the level of the different pollutants present in the air. These are nitrogen dioxide (NO2), particulate matter (PM2.5 and PM10), ozone (O3), nitric oxide (NO), oxides of nitrogen (NOX), and sulphur dioxide (SO2).

The structure of the relationship between exacerbation related COPD admissions and the variables mentioned above were explored on a weekly, bi-weekly, and monthly basis. Lag effects of the conditions (e.g., SI level, number of COVID-19 cases), i.e., 7 and 14 days, were also considered as the impact of these variables on the exacerbations might emerge after a period of time. Based on weekly admissions, a strong negative correlation between the number of COPD admissions and SI (-0.80) is observed. The association between COVID-19 outcomes (ranged -0.54 and -0.34) and exacerbation was weak. On the other hand, higher air pollutants were found to be associated with more admission (moderate estimate up 0.61). The correlation estimates for a weekly basis are given in Table 1.

Table 1 Correlation estimates between exacerbations related COPD admissions and the variables of interest

Variables (weekly)	N	Correlation Estimate	P-Value
COPD admission (a week ago)	100	0.91	<.0001
COPD admission (two weeks ago)	100	0.81	<.0001
Stringency index (SI)	100	-0.80	<.0001
COVID-19 case	100	-0.43	<.0001
COVID-19 admission	100	-0.54	<.0001
COVID-19 death	100	-0.47	<.0001
Temperature	100	-0.07	0.52
Nitric oxide (NO)*	100	0.60	<.0001
Nitrogen dioxide (NO2)*	100	0.58	<.0001
Oxides of nitrogen (NOX)*	100	0.61	<.0001
Sulphur dioxide (SO2)$^{\#}$	100	0.09	0.403
Ozone (O3)$^{\#}$	100	-0.21	0.036
PM10$^{\#}$	100	0.13	0.205
PM2.5$^{\#}$	100	0.16	0.145

Note: Air quality monitoring stations in Camden: *Holborn, $^{\#}$Bloomsbury

Following the correlation analysis, a multiple regression was carried out to estimate the number of COPD admissions. The structure of the relationship is given below in Eq.1 (adjusted R square of 0.83 and p-values of coefficients below <.0001).

$$\mathbf{COPD\ Admission\ (t)} = 1.578 + 0.689 * COPD\ admission(t-1) \\ +0.014 * \ Nitrogen\ dioxide\ (t) - \ 0.01 * Stringency\ index\ (t)$$

(Eq.1)

The equation suggests that the total number of exacerbation related COPD admissions at the current week is dependent on previous week`s admissions, plus a multiplicative factor of the average NO2 level at present week, less a fraction of the SI at the current week (on average). Weekly basis estimates were chosen for the regression model as their statistical outputs were superior to bi-weekly and monthly basis. Some air quality parameters including temperature were insignificant in estimating exacerbations. The regression model above is embedded in the simulation model as inputs regarding the number of COPD admissions, taking into account the different scenario settings.

Patient and public involvement

There was no patient or public involvement in the conduct of the study.

3. Results

Experimentation

The COPD simulation model was statistically validated for the year 2020/21, comparing the results generated by the DST with data observed at RFH. The outputs were within 5% on either side of real data, which confirms the validity of the model, endorsing use in practice.

The simulation period was set and run for 1 year (01st January 2022 – 31st December 2022). Four different scenarios were selected considering the UK government`s plan for COVID-19 related restrictions. Appointment types for outpatient clinics and services, referral and capacity rates for LF testing are adjusted to reflect the restriction level on a weekly/monthly basis during the simulation period. Table 2 shows the summary of the parameters in each scenario with approximate values. Note that the parameters in the scenarios are varied for each week/month. The details of the scenario settings are available in the supplementary file (see Table S1 and S2).

Benchmark scenario simulates an environment, where there are no restrictions and services run as usual (pre-pandemic), i.e., the year 2019. This is a scenario for comparison and to better understand the impact of COVID-19 on COPD services and patient outcomes. *Scenario 1* investigates mild restrictions in line with the UK government`s Plan A. *Scenario 2* includes stricter restrictions, e.g., face masks, work from home, which is the government`s Plan B.

Scenario 3 considers the possible situation where tougher restrictions could be imposed, under Plan C, involving, for example, closure of non-essential businesses.

Table 2 Some of the parameters in the scenarios

	Benchmark Scenario	**Scenario 1 (Plan A)**	**Scenario 2 (Plan B)**	**Scenario 3 (Plan C)**
Stringency Index (SI)	0	Between 20-25	Between 20-40	Between 20-60
Appointment Type (on average)	F2F: 100% Remote: 0%	F2F: 70% Remote: 30%	F2F: 50% Remote: 50%	F2F: 40% Remote: 60%
Referral Rate to LF Testing	Between 40%-45%	Between 15%-20%	Between 8%-12%	Between 2%-4%
PR Programme Type (on average)	F2F: 100% Remote: 0%	F2F: 25% Remote: 75%	F2F: 15% Remote: 85%	F2F: 0% Remote: 100%

The main driver of the scenarios is SI which affects (i) offered appointment type (F2F or remote), (ii) exacerbations via admission model, and (iii) service capacity and referrals. For example, relaxing restrictions during the summer period will lead to more F2F visits, in contrast to more remote clinics in the winter period due to tighter restrictions. The average splits between F2F and remote clinics are as follows: 100/0, 70/30, 50/50, and 40/60 for the scenarios, respectively. A hybrid blended approach is adopted for the ongoing delivery of the PR programme. PR is usually carried out in groups of 10-15 patients, increasing the risk of COVID-19 transmission, as a result, remote PR was initially the preferred option (i.e., home-based).

Referral rates and capacity of LF testing are also included in the scenarios as these are impacted by the COVID-19 restriction plans. For example, due to service disruption, referral rates are reduced from 40%-45% (pre-pandemic) to around 8%-12% under Scenario 2. Note that the scenario parameters can be tailored just like the input parameters by users depending on their settings and projections.

Model Outputs

The model was developed and tested at RFH and four different scenarios were run over a period of 1 year (excluding the warm-up period of six months). The DST can generate various outputs around service and patient outcomes. The service outputs are given for each scenario in Table 3.

Table 3 Service Outcomes

	Benchmark Scenario	**Scenario 1 (Plan A)**	**Scenario 2 (Plan B)**	**Scenario 3 (Plan C)**
Outpatient Clinics Outputs				
No. of Face-to-face Appointments	1226.5	856.1	615.7	484
No. of Remote Appointments	0	370.4	610.8	742.5
The Quality of Clinic Visits				
Worse than a usual appointment	106.2	292.1	412.7	481.1
Same as a usual appointment	744.9	567	451.4	385.4
Better than a usual appointment	205.7	197.7	192.7	190.3
Lung Function Testing Outputs				
No. of Referrals	515.8	195.5	113.0	29.9
No. of Attendance	330.7	134.2	80.0	22.8
No. of Patients on the Waiting List	148.7	47.1	22.9	4.7
No. of Did not Attend	36.4	14.2	10.1	2.4

More face-to-face appointments are expected as restrictions eased in Scenario 1 (856.1) compared to Scenario 2 (615.7) and Scenario 3 (484). The appointment type (F2F or remote) can affect the appointment quality, in the means of engagement between patient and clinician, patient's familiarity with technology, and self-expression. The appointment quality is benchmarked with a usual appointment for being worse, same, or higher, based on clinician perception of quality via our Twitter survey. 567 appointments in Scenario 1, 451.4 in Scenario 2, and 385.4 in Scenario 3 went at a quality level that would be expected at a usual appointment (see Table 3). Moreover, the number of appointments that went worse than a usual appointment are 292.1 in Scenario 1, 412.7 in Scenario 2, and 481.1 in Scenario 3. As a result, the figures show that clinic visit quality in Scenario 1 is marginally better than Scenario 2 and 3.

The other important finding is that the number of LF tests is impacted by the level of restrictions. Around 330 patients (out of 516 referrals) could be tested under the benchmark scenario considering the current backlog. This drops to 134, 80, and 23 of the referred patients under scenarios 1,2, and 3, respectively. The results show that the backlog in the system will take some time to clear even if the restrictions are fully lifted.

In addition, the model generated patient-related outcomes (amongst 1,600 COPD patients) considering the impact of COPD services and exacerbation (see Table 4). The simulation combined with the admission model showed the change in exacerbation related outputs depending on the scenario settings. The lowest values related to COPD exacerbation inpatient outputs (284 admissions and 1707 bed days) were in Scenario 3 where the stricter restrictions were set, whereas the benchmark scenario had the highest values (395 admissions and 2344 bed days) as SI was set to the minimum level. Lastly, the number of deaths in the hospital was quite close under the different scenarios and varied between 25 and 20 deaths.

Table 4 Patient Outcomes

	Benchmark Scenario	**Scenario 1 (Plan A)**	**Scenario 2 (Plan B)**	**Scenario 3 (Plan C)**
Exacerbation related Outputs				
No. of Admissions	395.1	327.8	305.2	284.1
No. of Used Bed Days	2344.4	1972.6	1830.0	1707.2
No. of Deaths	25.4	24.9	23.6	20.5
Change in QALYs				
via LF Testing	2.39	0.84	0.46	0.11
via PR	2.25	2.93	3.03	2.84
via Exacerbation	-22.77	-18.89	-17.59	-16.37
Total Change in QALYs*	**-18.14**	**-15.13**	**-14.10**	**-13.42**

*The total represents COPD management related QALY changes and does not include changes in mental and physical health due to the restrictions.

With regard to the impact of COPD patients' management on QALYs, the results indicate that the positive change in QALYs via LF testing under the benchmark scenario (2.39) is remarkably higher than under scenarios 1,2, and 3 (i.e., 0.84, 0.46, and 17 and 0.11, respectively) driven by the high number of referrals and attendances. LF testing itself can only improve patient outcomes indirectly, such as by identifying patients needing institution, or changes in therapy. As such, the availability of up-to-date LF testing results will enable clinicians to have a better understanding of a patient`s condition and better ability to offer treatment accordingly.[27]

For PR related QALYs, there is a slight variation in the values under different scenarios, all higher than the benchmark. This is due to changes in the split in F2F/remote service delivery and attendance/completion rates depending on the restrictions. However, QALYs loss after exacerbations is considerably high under the benchmark (-22.77) as compared to other scenarios. This is due to the relationship between exacerbations, the SI, and other factors such as hygiene, shielding, and air pollution.

Although restrictions and COVID-19 have significantly disrupted service delivery, the reductions in exacerbations and exacerbation related deaths are favourable outcomes for COPD patients. Therefore, the results show that fewer QALYs would be lost (in terms of the course of COPD and disease management) during more severe restriction periods, i.e., -13.42 for Plan C (Scenario 3), -14.10 for Plan B (Scenario 2), -15.13 for Plan A (Scenario 1), and -18.14 if there are no restrictions (Benchmark scenario). On the other hand, the shielding, stricter restrictions, and uncertain future regarding the pandemic might affect wider COPD patients` psychology (i.e., mental health, anxiety, depression) and physical health. These aspects are not covered in the present study as the model focuses on COPD management related outputs. A more holistic approach integrating the impact of COVID-19 and restrictions on physical and mental health of COPD patients would be necessary to capture patient outcomes more completely.

4. Discussion

This research explores the impact of coronavirus restrictions on COPD patients and services to inform stakeholders' (e.g., policymakers, clinicians, and service managers) decision making. The results of the DST tool demonstrate that although a reduction in restrictions increases the number of exacerbations, it opens up the opportunity to refer more patients to LF testing and provide F2F visits, which increases the quality of appointments.

The total change in patients` QALY after a year in terms of COPD related incidences (service and patient outcomes) was less under the scenarios where restrictions are tighter. COPD exacerbations, which immensely affect patients' QALY and may lead to readmissions or death, are the main drivers of these outputs. The study provided a snapshot of the service and does not imply that restrictions and shielding are beneficial for COPD patients in a holistic sense, despite the profound reduction in exacerbations and hospitalisations. Note that the study focuses on COPD related outputs and has not considered other factors, which may impact QALY such as the impact of the pandemic and restrictions on mental and physical health and the possibility of co-infection with COVID-19.

During restrictions, hospitals generally offered remote services by telephone or availability of digital technology. However, key services like LF testing needs to be conducted on-site, hence this particular service was either discontinued or immensely reduced. Looser restrictions lead to higher capacity in the service and a reduction in waiting times for LF testing. The results show that the backlog in this service will take some time to clear even once COVID-19 related restrictions are fully lifted.

Our survey amongst UK clinicians involved in COPD care questions the appointment quality in remote clinics. The survey pointed out that about 70% of remote clinic appointments had a quality worse than the usual F2F appointment (Only 17% had a better quality than the usual F2F appointment). Clinicians noted that remote visits may be better for some and worse for others. In addition, regarding the comparison between F2F and remote services, a study showed that home-based PR increase QALYs at a similar level compared to hospital-based treatment.[24]

Our analysis showed a strong negative correlation between the number of COPD admissions and SI (-0.80). This is because the COVID-19 preventative measures led to less exposure to bacteria, viruses, and air pollution. In addition, less SI was found to be associated with higher NO2 in the air, where the correlation analysis showed (-0.4). However, against this positive effect of restrictions, it is important to note that restrictions and shielding may cause anxiety and depression affecting mental health adversely.

COPD services have faced immense challenges through the COVID pandemic and continue to do so. Recovering services to pre-pandemic capacity is a key priority if we are to deliver on the respiratory aspects of the NHS Long Term Plan. Services are changing rapidly, as the pandemic evolves, and some aspects of care introduced during the pandemic will likely be retained, for example, greater opportunities for remote care where this does not affect quality. Although COVID-19 is likely to become endemic, the tool will still be useful in the case of future waves or pandemics or when testing the impact of change in delivery methods (e.g., remote, F2F, hybrid, virtual reality, and metaverse).[35,36]

This study has some limitations and assumptions. Due to data unavailability, the following were excluded in the study: COPD patients` deaths due to COVID-19, risk of infection and the impact of COVID-19 (e.g., reduction in QALY, impact of long COVID, and disability).

Furthermore, the physical and psychological impact of shielding and restrictions on COPD patients and their experience in remote clinics are not considered.

More complex mathematical models including machine learning approaches can be developed for estimating the admissions, which require a detailed and retrospective data collection and data analysis. More specific scenarios with a particular interest in the bottlenecks of the service can be simulated, e.g., increasing the LF testing capacity by offering drive-thru testing. The impact of policies to improve the management of COPD patients can be evaluated via the tool with minor changes. As an example, increasing the use of community services, offering mobile health technologies to monitor patients closely, and preventing admissions by detecting exacerbations or readmission early are some possible scenarios. These issues can be considered in future work.

5. Conclusion

This computer-based DST will enable COPD services to examine how the latest developments in care delivery and management might impact their service during and beyond the COVID-19 pandemic. The model is generic and comprehensive enough to be used by other COPD services in the UK and more widely with only minor adaptations.

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The List of Figure Legend/Caption

Figure 1 The flow diagram of the decision support tool. *F2F: Face-to-face, LF: Lung function testing, NIV: Non-invasive ventilation, Physio: Physiotherapy, PR: Pulmonary rehabilitation.*

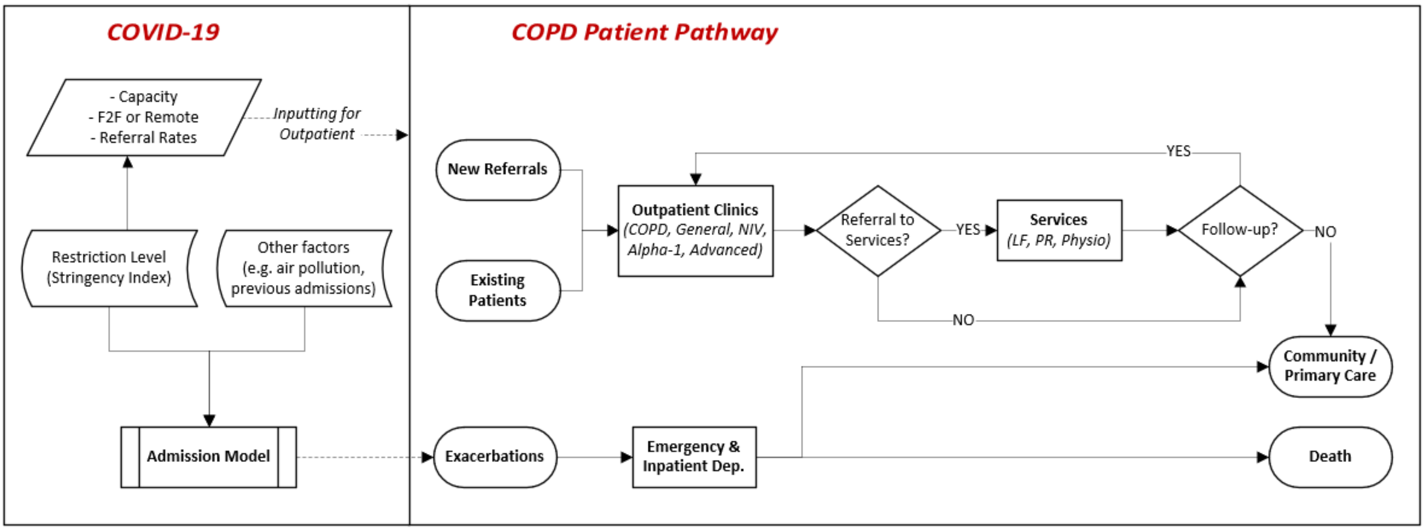

Figure 1 The flow diagram of the decision support tool. *F2F: Face-to-face, LF: Lung function testing, NIV: Non-invasive ventilation, Physio: Physiotherapy, PR: Pulmonary rehabilitation.*

Supplementary File

Table S1 Key Input Parameters of the Model

Input Parameter	**Estimate**
DEMAND	
Number of COPD exacerbation related arrivals to inpatient department	***The Admission Model*** *(i.e., Eq.1 presented in the manuscript)*
Number of new COPD patients seen in COPD service (weekly)	Uniform (6-9)
Number of existing COPD patients (for Follow-up appointment) seen in the service (weekly)	Uniform (16-22)
Percentage of new patients having a first appointment in each clinic	**COPD:** 32% **General:** 46% **NIV:** 13% **Alpha-1:** 4% **Advanced:** 5%
Percentage of existing patients having a FU Appointment in each clinic	**COPD:** 13% **General:** 66% **NIV:** 11% **Alpha-1:** 8% **Advanced:** 1%
Percentage of patients falling into each gender	**Male:** 52% **Female:** 48%
Percentage of patients falling into each age group	**25-44 years old:** 5% **45-54 years old:** 10% **55-64 years old:** 30% **65-74 years old:** 40% **75-84 years old:** 10% **85+ years old:** 5%
Percentage of patients falling into each disease severity	Mild: 10% Moderate: 40% Severe: 29% Very Severe: 21%
The capacity level for each clinic	**COPD:** Usual **General:** Usual **NIV:** Usual **Alpha-1:** Usual **Advanced:** Usual
OUTPATIENT DEPARTMENT	
Frequency of Clinic days	**COPD:** Once a week **General:** Once a week **NIV:** Once a week **Alpha-1:** Twice a week **Advanced:** Once a month
Attendance rate in each clinic	**COPD:** 75% **General:** 85% **NIV:** 85% **Alpha-1:** 95% **Advanced:** 95%
Appointment types for clinic visits, i.e., face to face or remote	***See Table S2***
Required mix of resources for Reception	**F2F:** A clerk and a desk **Remote:** none
Required mix of resources for Observation	**F2F:** An HCA and a room **Remote:** none
Required mix of resources for COPD and General Clinics	A consultant, an HCA, and a room

Required mix of resources for NIV Clinic	A consultant, an SV practitioner, an HCA, and a room
Required mix of resources for Alpha-1 Clinic	Two consultants, a HCA, a room, a scanner
Required mix of resources for Advanced Clinic	Two consultants, and an MDT, a room
Time spent in Reception per patient by appointment type (per patient)	**F2F:** Uniform (2-5 minutes) **Remote:** 0
Observation time in Observation room per patient by appointment type	**F2F:** Uniform (10-15 minutes) **Remote:** 0
Time spent in COPD Clinic and General Clinic (per patient)	**FA:** Uniform (30-45 minutes) **FU:** 15 minutes
Time spent in NIV Clinic and Alpha-1 Clinic (per patient)	**FA:** Uniform (30-45 minutes) **FU:** 20 minutes
Time spent in Advanced Clinic for First and FU appointments (per patient)	**FA:** 60 minutes **FU:** 20 minutes
Percentage of patients given a FU appointment in each clinic	**COPD:82%** **General:** 100% **NIV:** 80% **Alpha-1:** 95% **Advanced:** 45%
Waiting time for the next FU appointment (i.e., when the patient will come back)	**COPD:** 6 months **General:** 6 months **NIV:** 6 months **Alpha-1:** 6 months **Advanced:** 12 months
The quality of a clinic visit as a face to face appointment	**Worse than a usual appointment:** 10% **Same as a usual appointment:** 70% **Better than a usual appointment:** 20%
The quality of a clinic visit as a remote appointment	**Worse than a usual appointment:** 68,8% **Same as a usual appointment:** 14.3% **Better than a usual appointment:** 17.1%
OUTPATIENT SERVICES	
Percentage of patients referred to Physiotherapy and Pulmonary Rehabilitation	**Physiotherapy**: 15% **PR:** 5%
Percentage of patients referred to LF testing	***Benchmark:*** Between 40-45% ***Scenario 1:*** Between 15-20% ***Scenario 2:*** Between: 8-12% ***Scenario 3:*** Between 2-4%
Appointment types for Physiotherapy and Pulmonary Rehabilitation, i.e., face to face (centre-based) or remote (home-based)	***Benchmark:*** 100% F2F ***Scenario 1:*** 25% F2F, 75% Remote ***Scenario 2:*** 15% F2F, 85% Remote ***Scenario 3:*** 0% F2F, 100% Remote
Appointment types for LF testing, i.e., face to face or remote	100% Face to Face, 0% Remote
The capacity level in Physiotherapy and Pulmonary Rehabilitation	**Physiotherapy**: Usual **PR:** Usual
The capacity level in LF Testing	***Benchmark:*** 100% ***Scenario 1:*** 50-60% ***Scenario 2:*** 20-30% ***Scenario 3:*** 5-15%
Attendance rate for each service	**LF Test:** 90% **Physiotherapy**: 80% **PR:** 69%
Completion rate for Pulmonary Rehabilitation	42%
Required mix of resources for LF Test	A nurse and a room
Required mix of resources for Physiotherapy	A physiotherapist and a room

Required mix of resources for Pulmonary Rehabilitation	A physiotherapist, a nurse, a therapist assistant, a gym, and a classroom
Treatment time in each service	**LF Test:** 25 minutes **Physiotherapy**: Uniform (50-60 minutes) **PR:** Uniform (60-90 minutes)
Pre and Post assessment time in Pulmonary Rehabilitation (per patient)	Uniform (40-45 minutes)
Number of Pulmonary Rehabilitation sessions	16 sessions (2 sessions every week)
INPATIENT DEPARTMENT	
Length of stay in inpatient department	Frequency distribution (Average: 6.1 days)
Percentage of discharge method, i.e., Discharged to Community or PC, and Died.	**Community or PC:** 93% **Died:** 7%
PATIENT OUTCOMES	
QALY Gain due to PR	**F2F (Centre-based):** Uniform (0.029 – 0.032) **Remote (Home-based):** Uniform (0.037 – 0.040)
QALY Gain due to LF testing	Uniform (0.037 – 0.040)
QALY Reduction due to exacerbation related admission	Uniform (0.005 – 0.006)

Notes: Unless specified, the input estimates are the same for each scenario or all visit types. COPD: Chronic obstructive pulmonary disease, **FA**: First Attendance, **FU**: Follow-up, **F2F**: Face-to-face, **HCA**: Healthcare assistant, **LF**: Lung Function, **MDT**: Multidisciplinary Team, **NIV**: Non-Invasive Ventilation, **PC**: Primary Care, **PR**: Pulmonary Rehabilitation, **QALY**: Quality-adjusted life year, **SV**: Sleep & Ventilation.

Table S2 The parameter values of the scenarios

	Benchmark Scenario		**Scenario 1 (Plan A)**		**Scenario 2 (Plan B)**		**Scenario 3 (Plan C)**	
Month	**SI**	**Appt. Type (F2F, Remote)**	**SI**	**Appt. Type (F2F, Remote)**	**SI**	**Appt. Type (F2F, Remote)**	**SI**	**Appt. Type (F2F, Remote)**
Jan-22	0	100%, 0%	25	60%, 40%	40	40%, 60%	60	60%, 20%
Feb-22	0	100%, 0%	23	60%, 40%	40	40%, 60%	60	60%, 30%
Mar-22	0	100%, 0%	23	70%, 30%	40	50%, 50%	50	50%, 40%
Apr-22	0	100%, 0%	23	70%, 30%	35	50%, 50%	50	50%, 50%
May-22	0	100%, 0%	23	70%, 30%	35	50%, 50%	40	50%, 60%
Jun-22	0	100%, 0%	23	80%, 20%	35	60%, 40%	40	40%, 50%
Jul-22	0	100%, 0%	23	80%, 20%	23	60%, 40%	23	40%, 40%
Aug-22	0	100%, 0%	20	80%, 20%	20	60%, 40%	20	40%, 40%
Sep-22	0	100%, 0%	23	70%, 30%	23	50%, 50%	23	50%, 30%
Oct-22	0	100%, 0%	23	70%, 30%	35	50%, 50%	40	50%, 30%
Nov-22	0	100%, 0%	23	70%, 30%	40	50%, 50%	50	50%, 40%
Dec-22	0	100%, 0%	25	60%, 40%	40	40%, 60%	60	60%, 50%

Notes: Appt. Type: Appointment type, **F2F:** Face-to-face, **SI:** Stringency Index.