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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 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-related and service-related outputs. Thus, the likely impact of possible changes (eg, COVID-19 restrictions and pandemic scenarios) on patients with COPD 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 (among 1226 clinic visits) are expected in Plans A, B and C, respectively. Clinic visit quality in Plan A is found to be marginally better than in Plans B and C. Under coronavirus restrictions, lung function tests decreased more than 80% in Plan C as compared with 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 quality-adjusted life years (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.

STRENGTHS AND LIMITATIONS OF THIS STUDY

⇒ A decision support tool (DST) is developed to investigate the impact of COVID-19 measures on chronic obstructive pulmonary disease (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 (eg, 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.

INTRODUCTION

Due to restrictions to prevent the spread of COVID-19, the care and treatment for patients with chronic obstructive pulmonary disease (COPD) 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 (eg, lung function (LF) 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 with the prepandemic 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 in England experienced a significant decrease (ie, about 45%) in emergency admissions for

COPD, from 246.7 per 100 000 population in the financial year of 2019/2020 to 133.5 in 2020/2021.[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 (eg, healthier lifestyle, adherence to medicine), displacement of the primary admission diagnoses by COVID-19, and reduction in air pollution, such as nitrogen dioxide (NO_2).[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 of the restrictions. As of January 2022, the country recorded the highest cases since the outbreak started, that is, 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-19 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 (eg, quality of life, admissions). As there are no available data, this outcome does not include physical or mental health issues caused by the restrictions.

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 (eg, 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 policy makers. 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] Other DES studies include clinical outcomes,[14] redesigning patient pathways,[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 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 the study by Yakutcan *et al*[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 the Royal Free Hospital (RFH) and the Central and

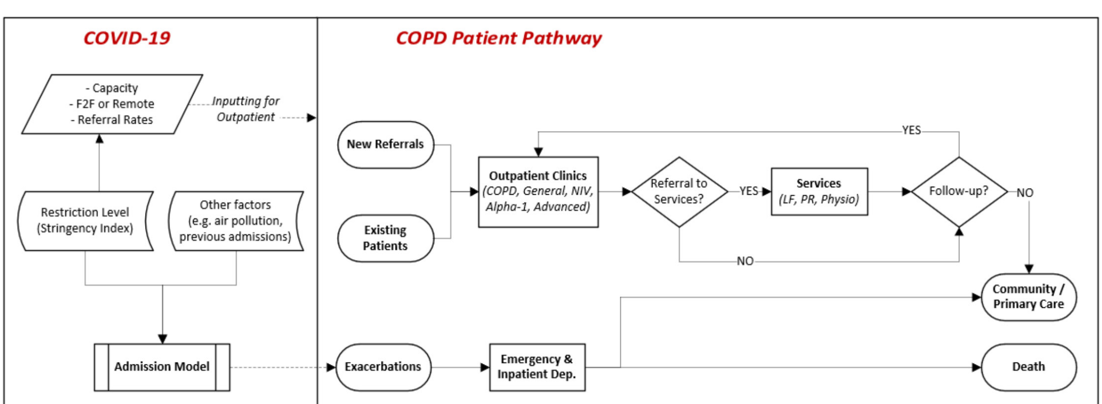

Figure 1 The flow diagram of the decision support tool. COPD, chronic obstructive pulmonary disease; F2F, face-to-face, LF, lung function testing, NIV, non-invasive ventilation, Physio, physiotherapy, PR, pulmonary rehabilitation.

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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 (LF testing, pulmonary rehabilitation (PR), physiotherapy), and emergency and inpatient departments. The pathway and simulation model are described in detail by Yakutcan *et al*.[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 patients with COPD to LF testing. On a positive note, the hospital's records showed 40% reduction in exacerbation-related COPD admissions during the pandemic compared with the previous year.

The DST

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 patients with COPD in the service and estimates the number of admissions (considering historical hospital data, restrictions and air pollution data), and 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 are higher than under stringent restriction.

The tool can generate a wide range of patient-related and service-related outputs including quality-adjusted life years (QALYs), number of hospitalisations and deaths, number of visits by appointment type (remote, F2F), 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 the national Hospital Episodes Statistics data set,[23] existing literature, online data sets, 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 F2F) as well as Stringency Index (SI), air quality, and COVID-19 outcomes. A full list of the input parameters is provided in the online supplemental 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 among healthcare professionals involved in COPD care in the UK. The participants were asked to compare their experiences in remote and F2F 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, for example, 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 2 years including a year before and a year during the pandemic, that is from 1 March 2019 to 28 February 2021.

The data were obtained from various data sources: (1) COPD admissions from RFH, (2) COVID-19 outcomes, that is, weekly cases and weekly deaths, were obtained from Camden Council's website,[32] (3) SI and new COVID-19 admissions were taken from the data set by the Oxford Coronavirus Government Response Tracker (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 were 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

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	<0.0001
COPD admission (2 weeks ago)	100	0.81	<0.0001
Stringency Index (SI)	100	−0.80	<0.0001
COVID-19 case	100	−0.43	<0.0001
COVID-19 admission	100	−0.54	<0.0001
COVID-19 death	100	−0.47	<0.0001
Temperature	100	−0.07	0.52
Nitric oxide (NO)*	100	0.60	<0.0001
Nitrogen dioxide (NO2)*	100	0.58	<0.0001
Oxides of nitrogen (NOX)*	100	0.61	<0.0001
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.
COPD, chronic obstructive pulmonary disease; PM, particulate matter.

pollutants present in the air. These are NO_2, particulate matter (PM2.5 and PM10), ozone, nitric oxide, oxides of nitrogen and sulphur dioxide.

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 (eg, SI level, number of COVID-19 cases), that is, 7 days 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 (range −0.54 to −0.34) and exacerbations was weak. On the other hand, higher air pollutants were found to be associated with more admissions (moderate estimate up 0.61). The correlation estimates for a weekly basis are given in table 1.

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 Equation 1 (adjusted R^2 of 0.83 and p values of coefficients below <0.0001).

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

(Equation 1)

The equation suggests that the total number of exacerbation-related COPD admissions at the current week is dependent on the previous week's admissions, plus a multiplicative factor of the average NO_2 level at the 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.

RESULTS

Experimentation

The COPD simulation model was statistically validated for the year 2020/2021, 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 (1 January 2022 to 31 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, and 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 online supplemental tables S1 and S2.

Benchmark scenario simulates an environment, where there are no restrictions and services run as usual (prepandemic), that is, 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, for example, 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.

The main driver of the scenarios is SI which affects (1) Offered appointment type (F2F or remote), (2) Exacerbations via admission model, and (3) 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

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	20–25	20–40	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	40%–45%	15%–20%	8%–12%	2%–4%
PR programme type (on average)	F2F: 100% Remote: 0%	F2F: 25% Remote: 75%	F2F: 15% Remote: 85%	F2F: 0% Remote: 100%

F2F, face-to-face; LF, lung function; PR, pulmonary rehabilitation.

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 (ie, 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% (prepandemic) 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 6 months). The DST can generate various outputs around service and patient outcomes. The service outputs are given for each scenario in table 3.

More F2F appointments are expected as restrictions eased in Scenario 1 (856.1) compared with 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. Five hundred and sixty-seven 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 in Scenarios 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 (among 1600 patients with COPD) considering

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 attendances	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

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.
COPD, chronic obstructive pulmonary disease; LF, lung function; PR, pulmonary rehabilitation; QALYs, quality-adjusted life years.

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.

With regard to the impact of management of patients with COPD 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 (ie, 0.84, 0.46, 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 lost after exacerbations is considerably high under the benchmark (−22.77) as compared with 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 patients with COPD. 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, that is, −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 the psychology of more number of patients with COPD (ie, 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 patients with COPD would be necessary to capture patient outcomes more completely.

DISCUSSION

This research explores the impact of coronavirus restrictions on patients with COPD and services to inform stakeholders' (eg, policy makers, 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 re-admissions 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 patients with COPD 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 among 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 increases QALYs at a similar level compared with 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 NO_2 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-19 pandemic and continue to do so. Recovering services to prepandemic 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 (eg, 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: deaths of patients with COPD due to COVID-19, risk of infection and the impact of COVID-19 (eg, reduction in QALYs, impact of Long COVID and disability). Furthermore, the physical and psychological impact of shielding and restrictions on patients with COPD 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 detailed and retrospective data collection and data analysis. More specific scenarios with a particular interest in the bottlenecks of the service can be simulated, for example, increasing the LF testing capacity by offering drive-through testing. The impact of policies to improve the management of patients with COPD 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 re-admission early are some possible scenarios. These issues can be considered in future work.

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.

Contributors Conception and design of study: UY, JRH, RL, ED. Acquisition of data: UY, JRH. Analysis of data: UY, ED. Model development: UY. Drafting and revising the manuscript: UY, JRH, RL, ED. Approval of the version of the manuscript to be published: UY, JRH, RL, ED. UY is responsible for the overall content as guarantor.

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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

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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.