



# Determinants in the adoption of a non-labor-substitution technology: mechanical ventilation in West Virginia coal mines, 1898–1907

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## Abstract

Accounts of technological change during industrialization processes based on labor-saving innovations are commonplace, even more so in the coal mining industry, in which the focus has until now been placed on the steam engine water pump and the coal cutting machine. However, to better understand technological change, we need to bear in mind the study of complementary capital. While previous research on complementary capital relies on evidence for manufacturing or the aggregate economy, this paper focuses on a case study, which provides more details on technology adoption decisions. This paper considers mechanical ventilation, a prominent and largely overlooked technology complementary to labor, as a response to stale air and explosions in the exploitation of coal. We examine the determinants in the adoption of the newer technology—the mechanical ventilator—through an economic model that is established at a high level of disaggregation: the mine. We concentrate on the West Virginia coalfield at the turn of the twentieth century, an apt historical setting for the study of technology adoption. We quantify characteristics of mines over time, so we are able to estimate a panel. We show the importance of various costs and benefits in explaining which type of mine converted from older technologies to the newer technology. The model is complemented with qualitative information, which helps to explain why an older technology slowed the process of adopting the newer as a result of different costs associated with the substitution.

**Keywords** Technology adoption determinants · Non-labor-substitution technology · Coal mining · Mechanical ventilation · USA

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John Murray died on March 27, 2018. Earlier drafts of this article were completed by the two authors previous to John's Death. I (Javier Silvestre) have written the revised version.

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## 1 Introduction

One of the most important current debates deals with the replacement of labor with capital. Comparisons with previous periods of intense technological change are prevalent. Accounts of the US and British industrial revolutions based on labor-saving biased technological change by Habakkuk (1962) and Allen (2009), respectively, are well known. It has also been argued that during the nineteenth-century industrial revolution the “displacement effect” tended to predominate over the “reinstatement effect.” That is to say, capital and new technologies substituted part of the labor and, therefore, labor demand tended to fall (Acemoglu and Restrepo 2019; Frey 2019). These interpretations, however, are not immune to criticism, as shown by several studies recently reviewed by Otojanov et al. (2020). One of the objections refers to exactly which individual industries or techniques the labor-saving framework may or may not be applied to, as saving capital and time as well as improving quality were targets of several new technologies (MacLeod 1988; Mokyr 2009, 2010; Kelly et al. 2014). Complementarities between capital and labor, in fact, have been a feature of the nineteenth and twentieth US industrialization processes (Goldin and Katz 1998; Katz and Margo 2014; Lafortune et al. 2019).<sup>1</sup>

From this point on, the contributions of this study to the literature on technology adoption during the industrial revolution are twofold. First, it considers a non-labor-substitution technology: the mechanical ventilation of coal mines as a major response to stale air and explosions. To better understand technological change, the evidence for labor-saving innovations needs to be supplemented with that of complementary capital. Previous research on complementary capital (as cited above) has tended to favor the analysis of manufacturing or the aggregate economy, whereas this paper aims to garner more detail on technology adoption decisions, focusing on a case study on coal mining.

To start with, we consider coal mining to be an industry which is typically thought of as crucially important for industrialization and economic growth in several European countries and the USA throughout the nineteenth century.<sup>2</sup> Traditionally, accounts of technological change in coal mining have put the emphasis on the horse, labor and fuel-saving steam engine water pump, and the labor-saving coal cutting machine (Greasley 1982; Dustmann 1986; MacLeod 1988; Fishback 1992; Boal 1994, 2017; Scott 2006; Allen 2009; Nuvolari and Verspagen 2009; Uchimura 2010; Nuvolari et al. 2011). As a result, the adoption of mechanical ventilation, a safety-related technology that was complementary to labor, has been largely overlooked. However, as pointed out by the British mining engineer and colliery manager Robert

<sup>1</sup> Wright (1990) emphasizes complementarity between capital and natural resources. Olmstead and Rhode (2008) refute the explanation of the primacy of labor-saving technology in agriculture.

<sup>2</sup> However, see Clark and Jacks (2007) and the works cited therein on coal of being of lesser importance.

L. Galloway (1882), once water drainage was resolved with pumping steam engines, explosions became one of the main concerns in the exploitation of coal. Ventilation was “the far more important and safer system” to reduce explosions in mines, stated a report by a reputable committee appointed to investigate the causes of accidents (The South Shields Committee 1843, p. 74).

Our second contribution is an economic model of the determinants in the adoption of technology, which uses a high level of disaggregation: the mine. The efficient rate of diffusion of a new technology is the subject of considerable debate. A priori it is not often clear how quickly entrepreneurs should adopt a new technology, and in fact, it has been found that a number of technologies, which ultimately became widespread, were slow to diffuse.<sup>3</sup> In contrast, our data show that the adoption of mechanical ventilation was relatively fast, even though a substantial number of mines stuck with the most common older technology. We are able to quantify characteristics of mines, and as a result consider which type of mines, driven by costs and benefits, converted from older technologies to the newer technology within a given time period. While decisions to convert to mechanical ventilation may have been made at the firm level, the actual installation took place at the pithead.

We trace the same mines over time. Variation in mine attributes makes identification, under certain assumptions, possible. To make the most of the panel-data nature of our source, and given that one of the key explanatory variables (firedamp) is time-invariant, we run correlated random effects (CRE) models. First proposed by Mundlak (1978), CRE models produce fixed effects by adding means of time-variant variables as regressors in random effects estimates (Wooldridge 2002, 2020; Allison 2009; Green 2012; Green and Zhang 2019). To confirm our findings, we perform a series of robustness checks in relation to sample size, model specification, location of mines, number of technological options, and potential endogeneity. We also explore the short-term effects of adopting mechanical ventilation.

Our empirical strategy is mainly based on information provided by inspectors in the State of West Virginia Department of Mines annual reports (hereafter WVDM). The same source has been exploited by Boal (2017, 2018) in his analyses of productivity and accidents.<sup>4</sup>

We also used a circular by the US Bureau of Mines (Forbes and Owings 1934) as a guide in the case of one of the explanatory variables (explosions). Additional, detailed, comments by mine inspectors, as well as descriptions of the suitability of ventilation technologies by contemporary engineers, help to enhance the understanding of the determinants of technology adoption. In this regard, we also utilized information provided by mine owners and miners appointed by the State governor (Joint Select Committee of the Legislature of West Virginia 1909). Overall, this is a

<sup>3</sup> A seminal study is that by Griliches (1957). See reviews of the literature by Hall (2005), Gruenhagen and Parker (2020) (for mining) and Juhász et al. (2020).

<sup>4</sup> Annual mine-level information has also been used by Jopp (2017) in his estimation of productivity in the Ruhr.

different approach within the cliometric literature on innovations, a field in which a large number of studies have used patent statistics (as reviewed by Khan 2013; Streb 2016; and Moser 2018).<sup>5</sup>

We focus on the West Virginia coal basin at the turn of the twentieth century, an appropriate historical setting for the comprehension of technology adoption, especially one related to safety. During that period, the coal basin started to undergo an intense process of growth and change, becoming the second state in terms of coal production—after Pennsylvania (US Geological Survey 1908; Dix 1977; Fishback 1992; Boal 1995; Rakes 1999). Its production ended up surpassing that of Belgium (in 1901) and France (in 1905) (Ministère de l'Intérieur 1904–1913; Ministère des Travaux Publics 1904–1913; Wright 1905). Furthermore, before the end of the first decade of the twentieth century explosions in West Virginia were comparatively high and on the rise. In a context of exceptionally vague and inadequate safety legislation, it is of interest to know how mine owners responded.

Our findings show that mine owners responded to a series of factors reflecting costs and benefits by adopting mechanical ventilation, which in fact was the most common recommendation made by inspectors. However, the acceptance of newer technology was not a clear-cut process. As a result, owners of several mines were put off of installing mechanical ventilation due to the costs associated with the change of method. In short, as is so often the case in the history of technology, the predominantly established method continued even after the newer one had become common (Engerman and Rosenberg 2016; Streb 2016).

The rest of the paper is organized as follows. Section 2 briefly discusses different ventilation technologies. Section 3 describes the West Virginia coal basin according to our objectives. Section 4 presents the data and the empirical strategy. Section 5 provides analyses of the determinants in the adoption of mechanical ventilation, adds several robustness checks, and discusses the results. Section 6 sets out our conclusions.

## 2 A brief history of ventilation

Better ventilation improved breathing conditions for underground miners.<sup>6</sup> The ventilation of mines was also the response to explosions caused, particularly, by methane gas or “firedamp”—a colorless and odorless gas that forms naturally alongside coal—and, sometimes, its interaction with coal dust—another inflammable agent. Explosions, and fires, were related to two main procedures pertaining to the extraction of coal: the lighting of mines and the use of explosives to release the coal from rock strata (e.g., Murray and Silvestre 2021).<sup>7</sup> Contaminated air would explode in the presence of a naked flame, from a candle or a safety lamp with the gauze removed. Lamps were also used to detect firedamp, as flames became blue and elongated in its presence, however they were, to some extent, inaccurate. Several kinds of explosives and ways of transmitting the charge to the explosive material were also prone to igniting ambient explosive materials. Safety lamps and explosives

<sup>5</sup> Although exceptions include Ciliberto (2010), Inwood and Keay (2012) and Juhász et al. (2020).

<sup>6</sup> In our setting, see especially WVDM (1883, 1891).

<sup>7</sup> A cornerstone of early research in explosions is Clayton (1739).

technologies improved over the course of the nineteenth and early twentieth centuries (Silvestre 2022). However, the relatively narrow scope of these improvements gave rise to the need for ventilation systems to clear the air.

By the beginning of the nineteenth century, two methods were commonly used to ventilate coal mines: natural ventilation and furnaces (e.g., UK Parliamentary Papers 1853).<sup>8</sup> Natural ventilation was based on the variation in temperature from outside to inside the mine enabling a steady flow of air.<sup>9</sup> Natural ventilation, however, worked in only the simplest of mines. As mines became bigger and/or deeper, and more intricate, natural ventilation became more variable and uncertain and, therefore, less reliable.

The artificial alternative to natural ventilation relied on heat. The baseline method placed a furnace near the bottom of a ventilation shaft (see Fig. 3a). The heat generated by the furnace reduced the air pressure immediately above it and drew stale air and firedamp from the connected galleries. Then, the warm air rose upward and on into the atmosphere (e.g., Hinsley 1969). Many safer and more productive variations and improvements were developed over time (Galloway 1882; Lupton 1893).<sup>10</sup> Furnaces were sometimes substituted by boilers and steam jets. However, this alternative to furnaces tended to be expensive and inefficient (Atkinson 1892; Wabner 1902).

The ultimate successor of furnaces and steam jets was the mechanical ventilator. Ventilation machines powered by steam engines worked on a variety of different principles.<sup>11</sup> Eventually, the centrifugal fan—as depicted in Fig. 3b—emerged as the most effective of these technologies (e.g., Cory 2005).<sup>12</sup> The earliest of these machines appeared in Belgium (1840) and Britain (1851), and then in Prussia (1856) (Preussische Schlagwetter Commission 1887; Murray and Silvestre 2015). US engineers may have started to pay attention to innovations in Europe in the mid-1850s (Wallace 1987). The USA being at first a follower country, this was common to other technologies (Khan 2013). The first mechanical ventilator in the Pennsylvania anthracite fields was installed in 1858 (Wallace 1987). The precise date for West Virginia, which developed later, is not known, but the first mine inspectors' annual report, in 1883, referred to only one instance of mechanical ventilation in operation (WVDM 1883).

### 3 The West Virginia coal basin at the turn of the century: growth, safety and ventilation

The first record of coal in the Appalachian fields was in West Virginia, together with Maryland, in 1736, and within a century coal had been discovered in many parts of the state (Eavenson 1942). The production of coal and the number of workers in the basin grew over time—as shown in Fig. 4. Little machinery was required in early

<sup>8</sup> Further early methods included man-made waterfalls.

<sup>9</sup> All methods of ventilation required two entrances into the mine.

<sup>10</sup> Furnaces were also cheap in terms of operating costs, as small coal that was difficult to sell served as fuel (e.g., Galloway 1878; Kerr 1901).

<sup>11</sup> Descriptions of human, animal or water-powered mechanical mine ventilation appear as early as in the sixteenth century (Agricola 1556).

<sup>12</sup> Although at first not necessarily the least expensive, as shown in Sect. 5.3.

mines, but the mechanization of coal cutting and haulage advanced from the turn of the century onward (e.g., Dix 1977; Boal 1995).

Explosions in West Virginia before the early 1910s were overrepresented as a cause of death. A comprehensive data collection by Fay (1915) shows that, between 1885 and 1913, explosions in the USA as a whole were responsible for 13.9 percent of total fatalities at coal mines, causing 4.6 fatalities per 10,000 workers per year. By contrast, in West Virginia, explosions were responsible for 21.8 percent of total fatalities, causing 10.9 fatalities per 10,000 workers. The deterioration of safety accelerated between the late 1890s and 1907, as shown in Fig. 1.<sup>13</sup> The absolute number of explosions and fatalities reached highs of 21 and 501 in 1907.<sup>14</sup> 1907 was the year of the Monongah 6 & 8 mine disaster, the deadliest in US coal mining history, which (officially) killed 362 miners (McAteer 2014; Brnich and Kowalski-Trakofker 2010). The difference between West Virginia fatality due to explosion rates and the national average subsequently fell (Boal 2018).

Rather than distinct geological conditions, the deficient regulation of safety (in general) and ventilation (in particular) seems to be the biggest determining factor in explaining the poor performance of the West Virginia coal basin.<sup>15</sup> Scholars have argued that the stiff competition within the industry, in which (despite the presence of a few large companies) small-scale mines predominated, forced an emphasis on production and avoidance of extra, safety-associated, costs on the part of both mine owners and managers (Graebner 1976; Dix 1977; Eller 1982; Fagge 1996; Uchimura 2010).<sup>16</sup>

West Virginia's first mining law was enacted in 1883. However, safety measures before 1908 were few and, in general, loosely enforced, probably making West Virginia the worst US state in these terms (Graebner 1976; Fishback 1985; Boal 2018). The number of inspectors was insufficient, in comparison with other states, and required inspections were not always carried out (Graebner 1976). Moreover, inspectors had no power to make arrests. It was not until 1907 that an inspector was legally able to close a mine, most often for poor ventilation (Fishback 1992). However, even then companies would fight in the courts to reopen mines (Graebner 1976).

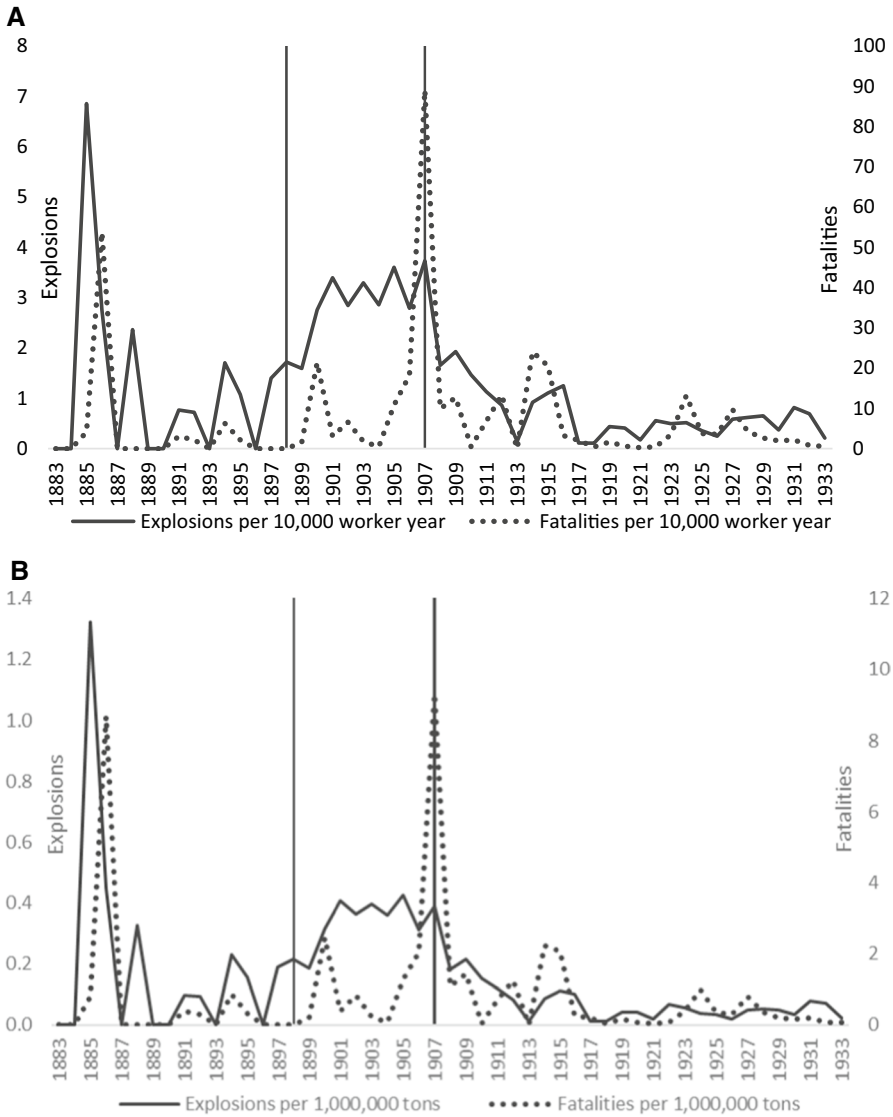
On a related note, before the workers' compensation law was enacted in 1913, companies were liable for accidents at the mine, which of course included explosions (Joint Select Committee of the Legislature of West Virginia 1909; McAteer 2014). However, in mining states employers' negligence was difficult to prove and attributing responsibility to miners was condoned by the legal system (Fishback 1987, 1992). Examples appear in the WVDM annual reports (e.g., 1905, 1907; see

<sup>13</sup> Because the denominators during the early years are low (see Figure A.2), extraordinarily high numbers of explosions (in 1885) and fatalities (in 1886) produce the first two spikes.

<sup>14</sup> The rise in explosions is steadier than the rise in fatalities. For the entire 1883–1933 period, the correlation between explosions and fatalities is 0.58.

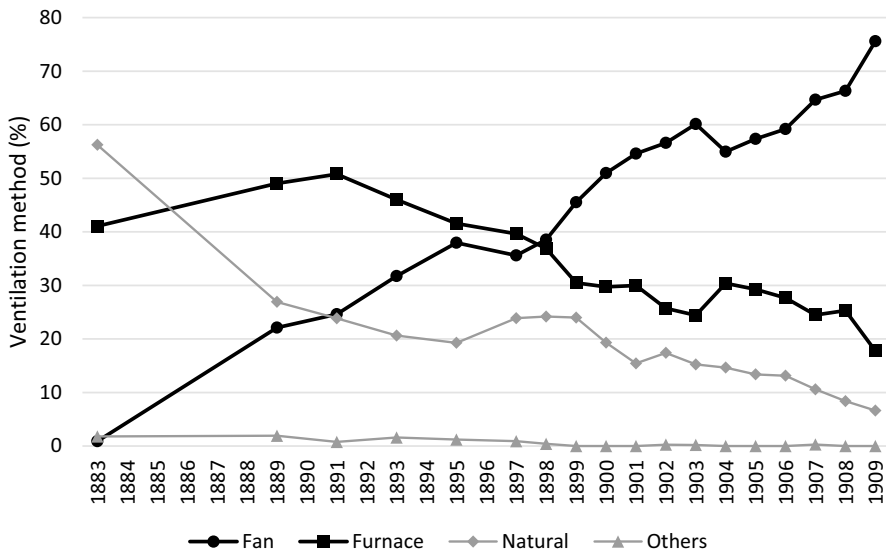
<sup>15</sup> On the effects of types of coal on explosions, see Rice (1910) and Graebner (1976).

<sup>16</sup> A careful examination of the behavior of two big owners reveals that safety, especially explosion related safety, was not their priority either, at least not before the end of the 1910s (Graebner 1976, pp. 142–146).



**Fig. 1** Explosions and fatalities due to explosions in West Virginia, 1883–1933, A. Per 10,000 worker year, B. Per 1,000,000 short tons mined per year. *Notes:* Firedamp and coal dust explosions. The two vertical lines delimit the period (1898–1907) for which the empirical model is estimated. *Sources:* Forbes and Owings (1934), for explosions and fatalities; West Virginia Office of Miners’ Health Safety and Training, <https://minesafety.wv.gov/historical-statistical-data/production-of-coal-and-coke-1863-2013/>, for employment and coal production

also Corbin 1981; Eller 1982). West Virginia inspectors asked for a clearer damages framework—similar to those established in Pennsylvania and Ohio (WVDM 1898). Voluntary payment on the part of West Virginia mine owners was perhaps



**Fig. 2** Relative use of ventilation methods (%) in West Virginia, 1883–1909. *Notes:* Data before 1897 are available for 1883, 1889, 1891, 1893 and 1895. *Sources:* WVDM (1883, 1889, 1891, 1893, 1895, 1897–1909)

uncommon (McAteer 2014). While insurance companies tended to be reluctant to assume the risk of insuring miners' lives (WVDM 1897, 1906).

As a result, miners and mine owners contributed to relief funds of different sorts (Fishback 1992; Fishback and Kantor 2000). Local union funds, company funds and hospital benefits funds were found in West Virginia by a US Commissioner of Labor (1909, pp. 201, 391, 623) report—as introduced by Fishback (1987). As an example, the agreement at the Macdonald Colliery included miners' dues, the company's contribution, disability (temporary) payments and death benefits (WVDM 1897).<sup>17</sup>

With specific regard to ventilation, firstly, West Virginia laws did not stipulate a particular threshold concentration of firedamp to mark the boundary between manageable and dangerous levels.<sup>18</sup> Rather, by 1898 (after some amendments), the state required each mine to supply at least one hundred cubic feet of fresh air per minute per miner (WVDM 1898). Concerns about the lack of stricter regulation were raised by the US Bureau of Mines and the US Coal Commission, as it was believed that many mines may have been incorrectly classified as non-gassy (Rice and Jones 1915; US Coal Commission 1925; Forbes and Owings 1934).

Secondly, the first law of 1883 and the revisions of 1898 and 1901 did not specify what to do in the case of firedamp being present, thereby leaving open the possibility

<sup>17</sup> For a more circumscribed burial fund, also at the company level, see Joint Select Committee of the Legislature of West Virginia 1909, p. 162). Large-scale explosions also attracted donations (McAteer 2014).

<sup>18</sup> In truth, this ambiguity was common to other US states and European countries.

of using a fan or other methods (WVDM 1901). This flexibility may have been in line with the owners' economic interests, but inspectors tended to hold a different stance—as also noted by the US Bureau of Mines (Forbes and Owings 1934). More often than not, the inspectors either expected and recommended or, in the case it were already in place, praised the use of mechanical ventilation. Two typical examples of this:

“[In the Ronda mine (Coalburg Colliery Co.)] The ventilation is produced by a furnace, but owing to the large development of the mine the furnace is too small to give sufficient ventilation (...) The assurance was given that a fan would be placed in the near future” (WVDM 1902, p. 201).

“Since the printing of the last report, this company [Shawnee Coal & Coke Co.] has replaced its old furnace by a fan, with a vast improvement to the ventilation” (WVDM 1895, p. 22).<sup>19</sup>

As a matter of fact, data available reported in Fig. 2 reveal that, despite the lack of legal requirements, mechanical ventilation was adopted rapidly. The share of mines with fans rose from one percent in 1883 to about one-fourth by the early 1890s and to 76 percent in 1909. Although West Virginia got off to a late start in coal production, the rate at which it adopted mechanical ventilation was not so different from that of the (also bituminous) coalfield in Pennsylvania, as shown in Fig. 5. However, turning to Fig. 2, at the end of the 1910s the furnace was still the preferred ventilation method in about 20 percent of the mines.

Legislation related to explosions was also inadequate. To begin with, coal dust was sometimes a key contributor to explosions (Aldrich 1995; Murray and Silvestre 2021). Thus, in the presence of coal dust, firedamp was inflammable or explosive at very low levels. In addition, coal dust on its own could potentially be ignited, for example by blasting. Explosions involving coal dust also tended to be of greater magnitude, as dust could propagate the initial explosion through the entire mine. It seems this applied to West Virginia (Rice 1910). A state law was passed in 1901 stipulating that coal dust must be sprinkled or rock dusted (Fishback 1992). However, it has been argued that the treatment of coal dust was limited to mines that generated gas “in dangerous quantities” (Corbin 1981). What is more, the practice of connecting mines for convenience of construction and transportation, but also thereby facilitating the spread of the explosion, had already been prohibited in some states, but not in West Virginia (McAteer 2014).

Certificates of competency for mine managers or certain types of miners were not required, unlike in some other US states (Dix 1977; Fishback 1992; Aldrich 1997). Untrained, sometimes foreign (non-English speaking), miners acted as shot firers (Rakes 1999; McAteer 2014). The use of “safety explosives” was first recorded in 1908 (Forbes and Owings 1934).<sup>20</sup> “Shooting off the solid” or blasting without previously undercutting the coal was a procedure employed as it raised miners' productivity. The problem was that this practice used large amounts of powder and, therefore, increased

<sup>19</sup> See also, for example, Joint Select Committee of the Legislature of West Virginia (1909, p. 579).

<sup>20</sup> The use of black powder instead, which was less safe but cheaper and more productive, may have been common (Aldrich 1995; McAteer 2014).

the risk of explosion (Aldrich 1997). Shooting off the solid was already prohibited in many countries and neighboring states, but permitted and apparently common in West Virginia. In 1906, an inspector declared that “a great many [miners] persist in doing such acts” (WVDM 1906, p. 400). Similarly, a report reviewing safety conditions concluded that “the practice of shooting off the solid [...] is still practiced to a large extent throughout the State” (Joint Select Committee of the Legislature of West Virginia 1909, p. 605).<sup>21</sup> However, the same report also recognized numerous companies in which this practice was not permitted and pursued. In fact, in its first reporting of shooting off the solid in 1911, the US Geological Survey (1912) reported that one percent of coal was extracted this way.

## 4 Data and empirical strategy

Our aim is to estimate the determinants in the adoption of the latest safety technology. We propose that the adoption of technology was a choice by coal owners, driven by associated costs and benefits. We start by means of quantifying the characteristics of mines, thereby determining which type of mines were more prone to adopt mechanical ventilation. We then (in the Discussion section) delve deeper into the mine owners’ possible motivations for substituting, or not, older technologies.

The period considered in our model is 1898–1907. Beginning in 1897 the state of West Virginia—in the WVDM annual reports—surveyed all mines that declared the employment of at least ten miners. However, data on explosions reported in the 1897 WVDM annual report do not match with those reported in the revision by the US Bureau of Mines (Forbes and Owings 1934), whose information we used as support. Therefore, we decided to skip the first year.<sup>22</sup> As of 1907, increasing numbers of mergers, acquisitions and mines being renamed meant that the share of mines providing necessary information, such as the ventilation method, that we were unable to match, grew substantially. The 1898–1907 years, nevertheless, correspond to a period in which fan adoption was taken up at considerable pace, against a background of economic expansion and lack of legal obligation (as seen above).

To estimate a panel, in principle, observations of the mine for at least two years from within the period are required.<sup>23</sup> Mines with only one observation-year have consequently not been used.<sup>24</sup> For all mine-year observations, the dependent variable was set equal to zero if the mine was still ventilated by natural, furnace or other

<sup>21</sup> See also (Graebner 1976), Rakes (1999) and McAteer (2014).

<sup>22</sup> Errors affected the recording of some early explosions, especially those related to the use of explosives (Forbes and Owings 1934, pp. 3–4; see also Graebner 1976, pp. 105–106). In any case, we extended the database one year backward to include 1897, and used the, presumably wrong, information on explosions reported in the WVDM annual report (Information by the US Bureau of Mines is reported at the county, rather than mine, level). Unreported results were similar to those shown in Table 2, with the specific exception of the explosions variable which became not significant.

<sup>23</sup> Below, in this section, we will return to this issue when introducing our first strategy to reduce potential endogeneity.

<sup>24</sup> These mines are added to an alternative sample (“c”) utilized as a robustness check (Sect. 5.2.1).

(usually steam) methods, and to one if the mine had converted to mechanical ventilation.<sup>25</sup> Nine mines have been dropped because they changed from mechanical to furnace ventilation.<sup>26</sup> There does not appear to be a clear profile of these mines, at least in terms of their quantifiable characteristics.<sup>27</sup> With two exceptions: they were non-gassy mines with practically no record of explosions (In the period considered, there was only one, apparently minor, explosion in one mine). Qualitative information provided by inspectors is not very helpful in this particular matter, as they did not seem to comment on the reasons for the substitution. One of these mines changed hands in the previous year (WVDM 1904, p. 165), whereas in another, the owner may have been experimenting with different ventilation methods (WVDM 1901, p. 203). We will return to this issue in Sect. 5.3.

Comments by inspectors throughout the annual reports suggest that fans and older technologies were mutually exclusive. In our sample, only eight mines with observations for at least two years reported having both a fan and a furnace. As in these instances a furnace was probably kept as a back-up, perhaps temporarily, we decided to set the dependent variable to one. Inevitably, the panel is unbalanced. As explained by Boal (2018), some relevant data affecting the variables were at times missed, and mines were sometimes unable to be matched across successive annual reports because the mine did not operate in all years or changed its name. The principal panel is comprised of 680 mines and 2,216 observations.<sup>28</sup>

Our main empirical analysis consists of the estimation of a logistic model, as a result of the dependent variable, fan adoption, being dichotomous. As a starting point, we relied on pooled specifications and random effects panel methods. Random effects models assume that unobserved effects are not correlated with explanatory variables. This may be a bold assumption. Mine specific characteristics such as geological conditions and management practices (which are not reported in the annual reports) are likely to be correlated with other explanatory variables—for example, productivity (Boal 2018). However, the gassy/non-gassy status of mines, a key explanatory variable, did not change over time (In technical terms, the within-variation of our firedamp variable is zero). Therefore, we also run correlated random effects (CRE) models. As explained above (in the Introduction), this approach estimates within effects in random effect models. In practical terms, this allows for the inclusion of time-invariant variables in what is effectively a fixed effects approach (Wooldridge 2020, p. 476). The rest of the explanatory variables vary over time.

<sup>25</sup> The use of steam jets and other methods was negligible. See Fig. 2.

<sup>26</sup> These mines are added to an alternative sample (“e”) utilized as a robustness check (Sect. 5.2.1).

<sup>27</sup> Specifically, variation is high regarding the year in which they changed ventilation method, the number of observation-years, the size of the workforce, coal tonnage, the share of output mined by machine, and seam thickness.

<sup>28</sup> The percentage of West Virginia coal mines included in our principal sample is: 58.37 (1899), 44.69 (1900), 45.35 (1901), 45.67 (1902), 46.89 (1903), 51.26 (1904), 55.29 (1905), 50.66 (1906), and 48.26 (1907). The percentages are higher for the alternative, and larger, sample “c” (1,225 mines and 3,667 observations) used as a robustness check in Sect. 5.2.1: 75.09 (1898), 79.77 (1899), 72.81 (1900), 76.34 (1901), 81.89 (1902), 80.08 (1903), 78.41 (1904), 79.15 (1905), 78.60 (1906), and 73.59 (1907).

Robust standard errors were clustered by mine in all specifications (Cameron and Trivedi 2010).

Table 1 describes the dependent and explanatory variables at mine level.<sup>29</sup> In our sample, 64 percent of the mine-year observations are for mines ventilated by fan. Explanatory variables reflect characteristics of mines associated with cost and benefit factors. To mitigate problems with endogeneity, each explanatory variable was assigned its value as of the previous year, which implies that observations of the mine for at least three years are needed.

An initial benefit to be derived from the adoption of mechanical ventilation is connected to the presence of firedamp. The percentage of gassy mines that suffered explosions in a year was: 21.05 (1898), 10.00 (1899), 8.70 (1900), 7.14 (1901), 7.14 (1902), 5.56 (1903), 15.79 (1904), 11.11 (1905), 10.81 (1906), and 14.71 (1907). As compared to the much lower percentages for non-gassy mines: 0.51 (1898), 1.01 (1899), 2.27 (1900), 1.58 (1901), 1.03 (1902), 2.51 (1903), 1.14 (1904), 1.27 (1905), 0.59 (1906), and 2.29 (1907). The expected effect of firedamp is therefore positive. 9.2 percent of the mine-year observations in our main sample are for mines considered to be gassy (Table 1). This proportion is not far from the 6.5 percent indicated by inspectors for 1897 (WVDM 1897). The number of gassy mines in West Virginia may, in fact, have increased during the very last years of the century—as also noted by one inspector (see Aldrich 1997).

A second benefit concerns explosions. Previous explosions at the mine provided information to mine owners about the probability of future explosions and the potential advantages of adopting mechanical ventilation. Thus, witnesses of explosions were examined “with a view if possible of determining the means by which these disastrous explosions may be prevented” (Joint Select Committee of the Legislature of West Virginia 1909, p. 816; see also Rakes 2008).<sup>30</sup> In this vein, after an explosion at the Berryburg mine (Southern Coal & Transportation Company), an expedition visited the mineworks to enquire about the causes (WVDM 1901, p. 88).<sup>31</sup> The expected effect of the number of explosions on the adoption of a more powerful, mechanical, ventilation system is then clearly positive.<sup>32</sup> We consider all explosions, comprising both explosions causing death and/or injury, as well as those with no casualties.

However, the extent of the impact of this variable is difficult to predict, as quantitative information on the cost of an explosion is scant. Explosions may have engendered high costs derived from the interruption of mining activity, and even the destruction of the mine, as stated by owners, miners and inspectors from several

<sup>29</sup> In 42 observations the number of declared workers was lower than ten. In this regard, see also Table 2 in Boal (2018, p. 136).

<sup>30</sup> On furnaces and explosions, see also, for example, Joint Select Committee of the Legislature of West Virginia (1909, p. 784).

<sup>31</sup> Mine managers collaborated with inspectors at accident sites (see also, for example, WVDM 1907, pp. 260–261).

<sup>32</sup> We refer to an alternative option to the number of explosions in Sect. 5.1.

basins (Aldrich 1995, 1997).<sup>33</sup> In his final report, the Joint Select Committee of the Legislature of West Virginia (1909, p. 820) points out that, after an explosion, “(...) the loss of thousands of dollars of property surely and unexpectedly follow.” Similarly, a group of West Virginia mine owners declared that:

“(...) putting aside all question of legal damages with the annoyance and expense of lawsuits, and coming down to cold blooded business facts, the mere delay and interruption of work in a colliery, caused by a single accident, is likely to cost more than the work that would have prevented it, while any serious disaster may cost thousands of dollars in labor and other thousands in the loss and interruption of business.” (Joint Select Committee of the Legislature of West Virginia 1909, p. 788).

The cost of one large explosion at Tucker County “to start [the mine] to work” (and before taking into account any possible lawsuits) was estimated at \$3,888 (Joint Select Committee of the Legislature of West Virginia 1909, p. 162). However, the total cost would have varied greatly from one explosion to another, depending on factors such as the magnitude of the blast and the awarding and extent of compensations.<sup>34</sup> Furthermore, explosions were statistically infrequent (see Fig. 1).<sup>35</sup> Most mines did not experience an explosion in a given year and the threat may have been a remote one (Aldrich 1995, p. 492). In our principal sample of 2,216 mine-year observations, explosions are only present in 48 of them.

The next potential benefit of adopting mechanical ventilation is related to the scale of the operation of the mine, which can be measured in terms of the size of the workforce.<sup>36</sup> Reports provide information on underground workers. There are two main reasons why large mines, which employed more miners, may have benefited from adopting mechanical ventilation. First, they required more fresh and fast-flowing air. As plainly written by an inspector,

“Sixty men are employed inside this [Roanoke] mine and six mules are used for hauling the coal. The ventilation of the mine is produced by a furnace which does not give a sufficient volume of air for the men working underground” (WVDM 1897, p. 198).<sup>37</sup>

Second, more miners meant a higher risk of explosions. “The most incompetent and unskilled miner establishes the safety within a mine,” declared a West Virginia inspector in 1907 (Aldrich 1997, p. 60). Perhaps it was more than that. Coal mining

<sup>33</sup> Mines that suffered explosions also appear to have had problems attracting workers (Aldrich 1997). The Consolidation Coal Co. Inc. concluded its advertisement to recruit 2,000 miners and helpers in the Monongahela Valley with the phrase: “Practically free from explosive gasses” (McAteer 2014, p. 74). Nevertheless, miners in West Virginia who worked the more dangerous jobs received higher wage premiums (Fishback 1984). See also, for example, WVDM (1906, p. 471).

<sup>34</sup> In the case of fatal accidents in West Virginia the average and median payments were \$560 and \$250, respectively, as estimated by Fishback (1992, p. 121). See also McAteer (2014, pp. 181–182).

<sup>35</sup> The absolute number of explosions was: 4 (1898), 4 (1899), 8 (1900), 11 (1901), 10 (1902), 13 (1903), 13 (1904), 18 (1905), 15 (1906), and 21 (1907).

<sup>36</sup> We refer to an alternative option in Sect. 5.1.

<sup>37</sup> See also, for example, WVDM (1902, p. 200).

**Table 1** Descriptive statistics. Sources: WVDM (1898–1907)

	Mean	Std. Dev	Min	Max
<i>Dependent variables</i>				
Mechanical ventilation (yes/no)	0.643	0.479	0	1
<i>Explanatory variables</i>				
Firedamp (yes/no)	0.092	0.289	0	1
Number of explosions	0.025	0.179	0	3
Number of (underground) workers/100	0.826	0.652	0.02	6.69
Share of output mined by machine	22.775	36.693	0	100
Productivity/100	7.728	4.294	0.052	65.118
Seam thickness (inches)	66.794	20.860	26	168

Period = 1898–1907. Firedamp is constant over time. Productivity = tons of coal produced / number of underground workers. Number of observations = 2,216 and number of mines = 680

was a complex endeavor involving a great deal of risk, which “depended on the behavior of everybody else” (Aldrich 1997, p. 54; see also Fishback 1992).<sup>38</sup>

One final benefit of installing a fan is related to the mechanization of coal extraction, measured as the share of output mined by machine. Early mechanization brought its own risks of explosion based on the contributing factors of production of coal dust and sparks (Rice and Hartmann 1939; Aldrich 1997; Rakes 1999; McAteer 2014). Moreover, mechanization in the West Virginia coalfield was fast. During the period considered in our model (1898–1907), the proportion of output mined by machine increased from 7.9 to 36.7 percent (US Geological Survey 1900; 1903; 1908).

Potential costs of the adoption of new technology must also be accounted for in the model. A priori, there is fair reason to expect a positive relationship between productivity and the adoption of mechanical ventilation. More productive mines would have found it easier to finance the installation of a fan, the upfront costs of which would have been high—as argued in Sect. 5.3 (see also Rakes 1999). We considered productivity to be measured as tonnage per (underground) worker.

With regard to further geological conditions (i.e., the presence of firedamp) of the mine affecting benefits or costs of technology adoption, the lack of information on depth is perhaps a limitation because ventilation may have become even more important as depth increased (e.g., Aldrich 1995). The WVDM reports, unfortunately, did not comment on this. This could have been the result of most mines being accessed by a drift, instead of a shaft, so depth was harder to define.<sup>39</sup> Reports do provide information on seam thickness, representing a further cost. Seam thickness, in reality, may have been a determinant of productivity (Young and Anderson 1957). The correlation between seam thickness and productivity in our main sample is 0.38

<sup>38</sup> One inspector’s (lengthy) reflection on interdependence and risk can be found in WVDM (1900, p. 318).

<sup>39</sup> I owe this remark to William Boal (Personal communication by email, July 27, 2018).

**Table 2** Adoption of mechanical ventilation in mines, 1898–1907. Logistic model

Dependent variable: adoption of mechanical ventilation in year  $t+1 = 1$  (0 otherwise)

	1	2	3	4	5	6
	Pooled	Pooled	RE	RE	Correlated RE	Correlated RE
	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx	dy/dx
<i>Benefits</i>						
Firedamp $t$	0.339*** (0.064)	0.100 (0.124)	0.353*** (0.046)	0.238* (0.105)	0.281*** (0.043)	0.149 (0.122)
Number of explosions $t$	0.264* (0.108)	0.258* (0.109)	0.221** (0.071)	0.219** (0.071)	0.139* (0.066)	0.139† (0.079)
Number of workers/100 $t$	0.337*** (0.033)	0.333*** (0.034)	0.271*** (0.036)	0.267*** (0.036)	0.136** (0.043)	0.133** (0.047)
Number of workers/100 x Firedamp $t$		0.488† (0.250)		0.219 (0.198)		0.049 (0.129)
Share of output mined by machine $t$	0.003*** (0.000)	0.003*** (0.000)	0.002*** (0.000)	0.002*** (0.000)	0.001** (0.000)	0.001** (0.000)
<i>Costs</i>						
Productivity/100 $t$	0.017*** (0.003)	0.017*** (0.003)	0.011*** (0.003)	0.010*** (0.003)	0.005* (0.002)	0.005* (0.002)
Seam thickness $t$	0.0004 (0.001)	0.0004 (0.001)	0.0003 (0.001)	0.0003 (0.001)	-0.002 (0.001)	-0.001 (0.001)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
No. of observations = 2,216						
No. of mines = 680						
F-test	13.23***	12.23***	4.63***	4.10***	3.48***	2.87***
Log pseudolikelihood	-1,013.05	-1,011.29	-689.59	-689.09	-664.35	-664.08

RE=random effects. Average marginal effects. Firedamp is constant over time. Cluster-robust standard errors at the mine level (in parentheses). All the regressions include an intercept term. †=significant at the 0.10 level; \* at the 0.05 level; \*\* at the 0.01 level; \*\*\* at the 0.001 level

(This is the highest correlation between our explanatory variables). We will consider the effect of this association in Sect. 5.1. Seam thickness may vary over time, presumably due to the change of seam within each mine (as shown by the data). The minimum and maximum values (Table 1) almost exactly correspond to the values for the coalfield, according to Cohen (1984).

Finally, time, annual, effects will be included in all the specifications as a proxy for decreasing costs of mechanical ventilation.

One potential limitation of our model is that we do not consider unionism to be a factor in the adoption of mechanical ventilation. Boal (2009, 2018), based on an

estimate of unionization from a collection of sources, shows that unionized mines tended to reduce fatality rates, especially for the 1897–1913 period. However, given the early difficulties faced by workers to organize themselves, the level of unionism for our period of study (1898–1907) tended to be low: zero percent before 1901, 6.5 in 1902, and around 13 percent afterward (Boal 1992, Fig. 1; 2006, Table 3; see also Fishback 1984, p. 758). Miners, in fact, may have preferred more powerful ventilation technology, in light of their complaints about furnaces as noted by inspectors (WVDM 1897, p. 50).

For the purposes of bolstering the results, our empirical analysis will include a series of robustness checks (in Sect. 5.2).

## 5 Results

### 5.1 Main results

The results of a model of new technology adoption are shown in Table 2. Average marginal effects are reported. All the estimated coefficients of variables tend to be significant at the usual levels, with seam thickness being the main exception. Signs are also consistent with each other across different estimates. In CRE estimates (columns 5 and 6), time-averages of explanatory variables (i.e., produced fixed effects) are not interpretable and therefore not reported. The results in columns 5 and 6 are plausible. In relation to columns 1–4, the magnitude of the estimated coefficients of all the variables is smaller—once the produced fixed effects have been added.<sup>40</sup>

With regard to variables reflecting benefits, in column 5, the identification of a mine as gassy increases the probability of adopting a fan by 28 percent. It is more than likely not by chance that mine owners reacted decisively to this factor. Inspectors made their point, clearly and repeatedly, that mechanical ventilation was the best way to cope with an unequivocal danger such as firedamp. For example, one stated that:

“In mines where there is fire damp the fan has a decided advantage over the furnace (...) The current produced by a fan is more regular than can be produced by a furnace” (WVDM 1889, p. 5).

Another inspector, in relation to the law leaving the means of ventilation completely open, explained that:

“(...) it is a well known fact that furnaces in mines generating explosive gas have been considered a source of danger (...) It is also a well known fact that furnaces are very unreliable sources of ventilating” (WVDM 1905, p. 241).

In columns 5–6, each explosion in the previous year increases the probability of adopting a fan by 14 percent. In further, unreported specifications, a binary variable, as an alternative to the number of explosions, was not significant. An additional lag

<sup>40</sup> A pertinent question would be if the estimated coefficients of time-variant variables (all but Firedamp) remain roughly the same when fixed effects, instead of “produced” fixed effects, are included. This is demonstrated by an unreported analysis.

of the explosions variable did not show an effect either. The difference between the extent of the “potential” effect of firedamp and the “real” effect of explosions may be striking at first. However, as argued above, explosions were ultimately quite a rare event, and perhaps no more expensive than installing mechanical ventilation. Moreover, mine owners blamed miners’ carelessness, in relation to various tasks, as a factor in the discussion on explosions, thus shifting the focus away from investment in costly safety devices (Graebner 1976; see also Corbin 1981).

The scale of operation, proxied by the number of workers, as expected, also influences the adoption of fans. Bigger mines required a more powerful ventilation technology. In columns 5–6, an addition of 100 miners (which is a figure close to the mean of 83, as reported in Table 1) leads to an increase in the probability of adopting a fan of about 13 percent. In columns 2, 4 and 6, interactions suggest that the effect of the size of the mine does not really depend on whether firedamp was present or not. Further, unreported, specifications, using the mine’s coal tonnage as an alternative measure of the scale of operation provided similar results to those in Table 2—except for the productivity variable, perhaps due to its high correlation, 0.55, with mine’s coal tonnage. The share of output mined by machine also have positive and significant effects on the adoption of mechanical ventilation. This result shows the importance of risks brought by early and rapid mechanization.

As for cost variables, productivity also has positive and significant effects on the adoption of mechanical ventilation. This result would appear to confirm the relationship between productivity and the ability to fund new technology. Seam thickness does not show an effect. In additional, unreported, regressions we removed seam thickness to find basically the same results for the productivity variable, as well as for the rest of the variables.

Finally, unreported time annual effects tend to show an increasing trend in the size of their positive influence—which becomes significant from 1903 onward.<sup>41</sup> Thus, this result would suggest that mechanical ventilation may have become more affordable over time.

## 5.2 Robustness checks

### 5.2.1 Alternative samples

A justified concern with our results is related to the nature of the sample, a set of matched mines that appear for at least two years within the period. Therefore, we first considered a series of samples to try to minimize the possibility of bias: (a) we replaced the main sample with a new, restricted, sample of mines reporting for all the years between 1898 and 1907, meaning they were continuously operating for the entire period; (b) we used a sample in which the “already treated” cases, that is to say, those mines that were mechanically ventilated for all the years covered,

<sup>41</sup> Alternatively, the use of a time trend variable implies that—in column 5—each year increases the probability of adopting a fan by 2.1 percent (significance at the 0.000 level). Similar values were obtained in the rest of the columns.

were removed. We did so to dismiss any possibility that the already treated cases may have been improving the precision of estimates; (c) we added the mines that only reported once, to obtain a larger pool—The results of this robustness check appear in Table 3; (d) we focused on the mines that only reported once. In two additional samples: (e) we added the (previously excluded) nine mines that changed from mechanical to furnace ventilation; and (f) we removed one observation-year, corresponding to the Monongah 6 & 8 mine explosion—an outlier in terms of its magnitude. Unreported results were similar to those shown in Table 2, with the main exception of the lack of significance of the number of explosions in the samples of mines reporting for all the years (a) or only once (d), presumably due to their small size (57 and 494 mines).<sup>42</sup>

### 5.2.2 Complementary model specifications

Here, we first estimated a linear probability model (LPM), a reasonable complement to the estimation of logistic models for binary response due to its inherent complexities (Wooldridge 2002). Then, we estimated a time to adoption model. Specifically, the Cox (1972) model which makes no assumptions on the shape of the “hazard” function—the probability of a mine adopting mechanical ventilation—over time. Results tended to be similar, with the main exception of the weaker significance of the number of explosions variable.

### 5.2.3 The location of mines

The probability of adopting a fan may also potentially be influenced by the place where the mine was located within the coal basin, due to, for example, the relative zeal of inspectors in their push for mechanical ventilation. The main results were also robust when we accounted for this, by means of a multi-level model that includes variation at the level of (27) counties.<sup>43</sup>

### 5.2.4 Three ventilation options

The estimation of our main model is based on the choice between two options: mechanical ventilation versus all other available methods, which were basically furnace and natural. Natural ventilation, already of relatively little importance at the beginning of our period of study (24 percent of mines in 1898), was marginal at its end (10 percent in 1907) (see Fig. 2). Inspectors, in fact, only recommended natural ventilation in “special cases,” usually referring to mines that were very small or

<sup>42</sup> All unreported analyses mentioned in this and previous sections are available from the authors upon request.

<sup>43</sup> Percentage distribution of observations: Barbour (1.53), Brooke (1.13), Clay (0.32), Fayette (22.61), Grant (0.23), Hancock (0.45), Harrison (8.39), Kanawha (13.94), Lincoln (0.27), Logan (0.54), Marion (6.23), Marshall (1.44), Mason (2.30), McDowell (14.67), Mercer (3.79), Mineral (2.35), Mingo (5.73), Monongalia (0.68), Nicholas (0.72), Ohio (1.67), Preston (2.75), Putnam (1.31), Raleigh (2.17), Randolph (0.95), Taylor (1.81), Tucker (1.99), and Upshur (0.05).

very short-lived (e.g., WVDM 1907). In any case, we estimated a multinomial logit model to lessen the assumption that the other methods (furnace and natural) can be put together in the same category. The CRE specification, in particular, performed worse than that in Table 2. However, in terms of signs and significance of variables, the general picture remains one of essentially no difference between natural and furnace, as compared to mechanical ventilation.

### 5.2.5 Potential endogeneity

Finally, our approach so far mitigates some problems of endogeneity because conversion of ventilation systems is observed only *after* the mine characteristics were identified. Still, it leaves open the question of how mines that were initially classified as having fan ventilation decided on that method in the first place. For many of the mines, there is no statistical method to answer this question, because we cannot know how old the mine was nor when it installed its fan. But there is a special case that addresses the question of the initial choice of fan ventilation: newly sunk mines. If we are willing to assume that the survey was complete (a bold assumption to be sure), then a mine that appears in a survey at time  $t$  but did not appear in time  $t-1$  must have opened in the interim. We can ask: what characteristics, among these mines, were associated with the *immediate* installation of mechanical ventilation? The results of specifications regarding this class of mines appear in Table 4 and are in line with the results in Table 2 (pooled columns 1 and 2). The weaker significance of the number of explosions (at the 0.141 level in column 1, Table 4) makes sense as this variable is not lagged.

## 5.3 Discussion

Our main specifications and robustness checks indicate that the mines that adopted mechanical ventilation tended to be firedamp-laden, have already suffered explosions, be of a bigger size, be more mechanized, and display higher productivity. An additional estimation reported in Table 5 (column 1) would suggest that the installation of fans actually decreased explosions, thereby confirming the efficacy of inspectors' recommendations. The Poisson coefficient (in column 1) of having adopted a fan in the previous year implies that the expected number of explosions would be about  $100((e^{-1.083})-1) \approx 66\%$  lower. However, as shown above (Fig. 2), the older furnace method was still common in the coalfield at the end of our period covered. In this section, the cost–benefit explanation for the persistence of an earlier technology is supplemented with additional evidence. Furnaces were sometimes preferred to fans due to three costs associated with their substitution.

First, despite inspectors' guidance, for some owners the decision may have been taken in a context of still relatively limited information on the advantages of the latest technology. Conversely, there was plenty of knowledge and experience regarding the older technology. How much volume of air per unit of time was an essential element to be considered (Galloway 1900; Shurick 1922). However, right up to the turn of the century fans tended to not always be more mechanically efficient than

furnaces. Experiment-based evidence in several countries (although difficult to compare) points to the late nineteenth century as precisely the moment in which furnaces reached their peak efficiency and mechanical ventilators increased theirs (Atkinson 1892; Lupton 1893; Clifford 1897; Wabner 1902). This came with the introduction of more advanced kinds of fans, such as the Guibal and Capell designs, whose popularity was rising in Europe and the USA (Murray and Silvestre 2015).

Second, installation costs tended to be much lower for furnaces than for fans. Across several sources, we have been unable to find quantitative evidence of the installation cost of fans at the West Virginia coalfield, with one exception. In Table 6, this estimate is put together with, still, more abundant estimates of ventilation methods from European sources. The term fan refers to those of Guibal and Capell types—the most frequently used in West Virginia. Estimates of installation costs for furnaces are mostly from Britain—where this (scarcer) type of information is more widely available (Wabner 1902). The West Virginia mine owner’s estimate of \$8,000 for a fan hovers in the mid-range. As a further reference, the average annual wage received per pick miner in West Virginia was \$643.05 (WVDM 1907, p. xxxiii).

Therefore, initial costs may have been a heavy burden for the average West Virginia mine, which was of small size (Rakes 1999).<sup>44</sup> West Virginia mine inspectors recognized this as a major cost factor in the adoption decision. For example, in one mine, “a fan was suggested as better [than a furnace] means of ventilation,” but the “expenses of a fan was considered unwarrantable [by the mine owner]” (WVDM 1901, p. 153). The need to build a power source, as purchased electricity was not available in rural West Virginia, may have contributed as well.<sup>45</sup> To put it succinctly:

“(…) if the first cost of installing a fan could be done as cheaply as a great many of the makeshift furnaces, I am satisfied there would not be a mine in the country without a fan” (WVDM 1905, p. 241).

Finally, mine owners may have also faced a high degree of uncertainty in relation to the use of the new technology, hence the continued use of furnaces in some cases. Having no moving parts, furnaces tended to be reliable enough not to warrant being replaced by mechanical ventilators with all the usual bugs (Atkinson 1892). More importantly, for a full and efficient use of the fan a host of technical problems requiring a high degree of skill needed to be resolved (Shurick 1922). As stated in a US Bureau of Mines circular, “In 1910, though a considerable amount of engineering knowledge was available, coal-mine ventilation was almost entirely on an empirical trial-and-error basis” (Fieldner 1950, p. 8). After all, the real test of a fan was if it worked in the opening to a particular working pit. Thus, the effectiveness of the fan depended not only on its strength and design but also on the aerodynamic drag

<sup>44</sup> Dix (1977) categorizes smaller mines as those employing less than 100 workers and producing less than 100,000 tons per year. In our main sample, the averages are 83 workers and 69,778 tons.

<sup>45</sup> I owe this remark to a reviewer. See also Rakes (1999) and Long (2010).

created by the unique characteristics of each mine (Rice and Jones 1915; Aldrich 1997).<sup>46</sup>

The improper use of ventilation in the West Virginia coalfield may have been commonplace (Graebner 1976; Rakes 1999). For example, fans frequently stopped because of power cuts, and they were also operated only when the miners were in the mine, which was an erroneous practice (Forbes and Owings 1934).<sup>47</sup> Fans also needed to be located in the right place. However, this was not always the case (Watteyne et al. 1908; Forbes and Owings 1934).<sup>48</sup> Inspectors comment on explosions in which the cause appears to have been incorrectly used ventilation.<sup>49</sup> This situation throws light on why some mine owners were wary of the new technology, as noted by one American engineer (Clifford 1897). Summarized by an inspector thus:

“(...) many fans here are rendered almost useless from a standpoint of effectiveness, by being carelessly, and I must say, ignorantly erected” (WVDM 1901, p. 113).<sup>50</sup>

## 6 Conclusions

A central issue in the economic history literature on technology adoption has been innovation induced by factor prices, often labor. This paper contributes to the literature considering a non-labor-substitution technology. Unlike most previous research on complementarity between capital and labor for the USA, which tends to adopt an aggregate approach, this paper has concentrated on a case study for the mining industry. This design not only allows more detail on technology adoption decisions, but also complements predominant accounts of technological change in coal mining, where the emphasis has been put on the water pump and the coal cutting machine.

This paper studies a prominent, and largely overlooked, technology which emerged and developed as the nineteenth century progressed: the mechanical ventilation of mines to improve working conditions and reduce the effects of inflammable agents, so common in carbonaceous settings. Mechanical ventilation made it possible to overcome the relatively low effectiveness of safety lamps and explosives in addressing the limiting problem of explosions.

The West Virginia coal basin at the turn of the century offers a fortuitous setting for the investigation of a safety-related technology. The coalfield underwent an intense process of growth and transformation, and also had a notorious record of unsafe practices and explosions. Beyond recommendation by inspectors, no institutional influence on technology adoption behavior was present, as there were no legal requirements with regard to particular ventilation methods.

By means of an economic model, we have proposed an examination of the determinants in the adoption of newer technology. Our evidence consists of mine-level

<sup>46</sup> On a similar note, an unintended consequence of fans was that, given their greater power, they tended to produce more coal dust that settled on walls and roof supports, which was more likely to explode than dust on the floor (Aldrich 1995; Murray and Silvestre 2021).

<sup>47</sup> See also, for example, WVDM (1898, p. 115).

<sup>48</sup> See also, for example, WVDM (1901, p. 141).

<sup>49</sup> Such as the Red Ash mine explosion, which caused 46 deaths (WVDM 1900, pp. 304–314), and the Berryburg mine disaster, which caused 15 deaths (WVDM 1901, pp. 88–95). See also McAteer (2014).

<sup>50</sup> See also WVDM (1889, p. 5; 1900, pp. 361–371).

observations, a high level of disaggregation that is still uncommon in the cliometric literature. Our analysis was carried out in two stages. We first quantified characteristics of mines and, within a panel-data framework, estimated the contribution of costs and benefits of technological change. The results help to delineate the type of mine that converted from previous ventilation methods to mechanical ventilation. To confirm our findings, the empirical approach included robustness checks of various types.

The adoption of the new technology was fast, which is not a typical finding. An additional analysis suggests that mechanical ventilation paid off in safety terms, which is in line with the stance by the mine inspectors. However, it is worth noting that fans had to compete with the established form of older technology, i.e., furnaces. In a second stage, we delved deeper into the substitution process by means of contemporary engineering literature, as well as mine owners, miners and inspectors' comments, in order to grasp better the motivations of mine owners for installing, or not, the new technology. For some mines, the traditional technology seemed to be reasonable, ultimately due to the various costs associated with the conversion.

## **Appendix**

See Tables [3](#), [4](#), [5](#), [6](#) and Figs. [3](#), [4](#), [5](#).

**Table 3** Adoption of mechanical ventilation in mines, 1898–1907, larger sample (Robustness check 5.2.1, “c”). Logistic model

Dependent variable: adoption of mechanical ventilation in year $t = 1$ (0 otherwise)		
	1	2
	Pooled	Pooled
	dy/dx	dy/dx
<i>Benefits</i>		
Firedamp $t$	0.336*** (0.050)	0.247* (0.104)
Number of explosions $t$	0.163** (0.061)	0.160** (0.061)
Number of workers/100 $t$	0.346*** (0.026)	0.344*** (0.026)
Number of workers/100 × Firedamp $t$		0.162 (0.167)
Share of output mined by machine $t$	0.003*** (0.000)	0.003*** (0.000)
<i>Costs</i>		
Productivity/100 $t$	0.018*** (0.003)	0.018*** (0.003)
Seam thickness $t$	-0.0002 (0.001)	0.0002 (0.001)
Year fixed effects	Yes	Yes
Number of observations = 3,667		
Number of mines = 1,225		
F-test	21.05***	19.74***
Log pseudolikelihood	-1,765.35	-1,764.65

Average marginal effects reported. Cluster-robust standard errors at the mine level (in parentheses). All the regressions include an intercept term. \* = significant at the 0.05 level; \*\* at the 0.01 level; \*\*\* at the 0.001 level

**Table 4** Adoption of ventilation in the first year of operation of new mines, 1899–1907 (Robustness check 5.2.5). Logistic model

Dependent variable: adoption of mechanical ventilation in year $t = 1$ (0 otherwise)		
	1	2
	Pooled	Pooled
	dy/dx	dy/dx
<i>Benefits</i>		
Firedamp $t$	0.343*** (0.077)	0.269* (0.136)
Number of explosions $t$	0.222 (0.151)	0.221 (0.151)
Number of workers/100 $t$	0.300*** (0.037)	0.298*** (0.037)
Number of workers/100 $\times$ Firedamp $t$		0.144 (0.205)
Share of output mined by machine $t$	0.003*** (0.000)	0.003*** (0.000)
<i>Costs</i>		
Productivity/100 $t$	0.013** (0.004)	0.013** (0.004)
Seam thickness $t$	0.0001 (0.001)	0.0001 (0.001)
Number of observations = 1,010		
F-test	13.40***	12.60***
Log pseudolikelihood	-519.49	-519.33

The year 1898 is not included. Average marginal effects reported. Cluster-robust standard errors at the mine level (in parentheses). All the regressions include an intercept term. \* = significant at the 0.05 level; \*\* at the 0.01 level; \*\*\* at the 0.001 level.

**Table 5** Effects of the adoption of ventilation technology in mines, 1898–1907

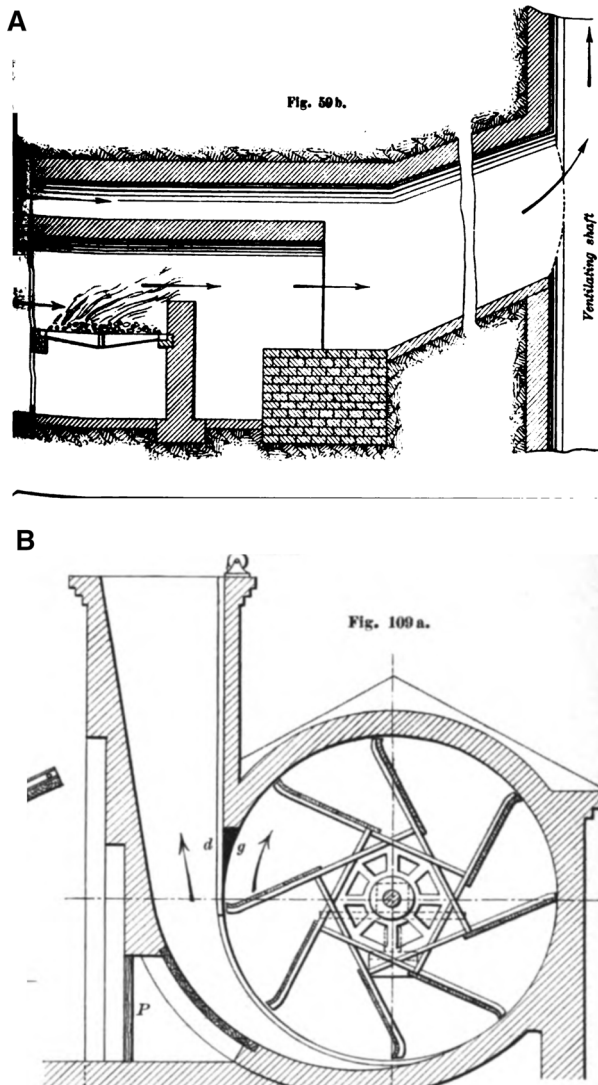
	1	2
	Number of explosions <sub>t+1</sub>	Productivity <sub>t+1</sub>
	Poisson	
	Correlated RE	Correlated RE
	Coefficient	Coefficient
Fan <sub>t</sub>	-1.083 <sup>†</sup>	0.373
	(0.637)	(0.257)
Firedamp <sub>t</sub>	1.564***	0.084
	(0.292)	(0.328)
Share of output mined by machine <sub>t</sub>	0.016*	0.009**
	(0.007)	(0.004)
Seam thickness <sub>t</sub>	-0.001	0.038**
	(0.029)	(0.014)
Year fixed effects	Yes	Yes
Number of observations = 2,216		
Number of mines = 680		
F-test	4.01***	31.15***
R <sup>2</sup>		0.265
Log pseudolikelihood	-238.95	

In column 1, the Poisson model is preferred to a negative binomial model because no overdispersion is indicated by the test proposed by Cameron and Trivedi (2000, p. 575). RE = random effects. In order to put the impact of fans in context, specifications in column 1 and column 2 include the same set of explanatory variables. Column 2 suggests that the impact of fans on productivity was weaker (significance at the 0.138 level). The number of workers was added in estimates for both specifications. However, perhaps due to its relatively high correlation with the fan variable, 0.42, the models performed worse. Firedamp is constant over time. All the regressions include an intercept term. † = significant at the 0.10 level; \* at the 0.05 level; \*\* at the 0.01 level; \*\*\* at the 0.001 level

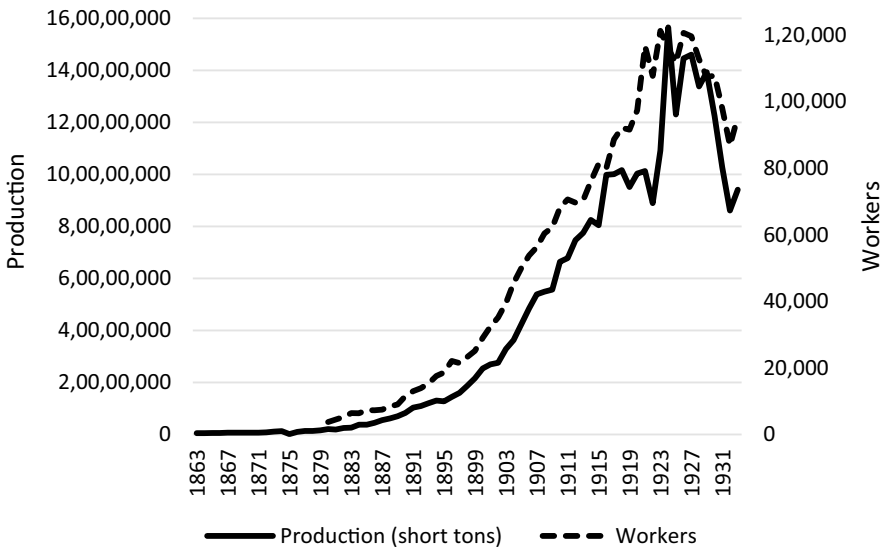
**Table 6** Initial costs of furnaces and centrifugal mechanical ventilators. A comparison. Sources: UK Parliamentary Papers (1853, p. 147); Mackworth (1856, p. 73); Atkinson (1892, p. 97); Mativa et al. (1892, p 76); Kerr (1901, p. 334); Wabner (1902, pp.180, 193); Joint Select Committee of the Legislature of West Virginia (1909, p. 587)

	Cost in \$1908
<i>Furnaces</i>	
In one British mine, c. 1850	192
Anzin (Pas-de-Calais), c. 1850	498
Tyne main colliery, c. 1850	810
In one British mine, c. 1900	1,359
<i>Centrifugal mechanical ventilators</i>	
Capell fan, Essen, 1889	4,260
Guibal fan, Westphalia, c. 1900	5,991
Guibal fan, Liege, 1891	6,290
Guibal fan, Hainaut, 1882	6,300
Guibal fan, Hainaut, 1877	6,663
Average of 4 Capell fans (locations are not available), c. 1900	7,067
Guibal fan in one German mine, c. 1900	7,176
Guibal fan, Hainaut, 1886	7,731
Capell fan, Gelsenkirchen, 1891	7,750
West Virginia, one mine owner's estimate, 1908	≈ 8,000
Average of 78 Guibal fans, Prussia, c. 1884	8,263
Guiban fan, Saarland, c. 1900	8,725
Capell fan, Westphalia, 1889	8,763
Capell fan, Hainaut, 1891	8,985
Guibal fan in one British mine, c. 1900	13,339

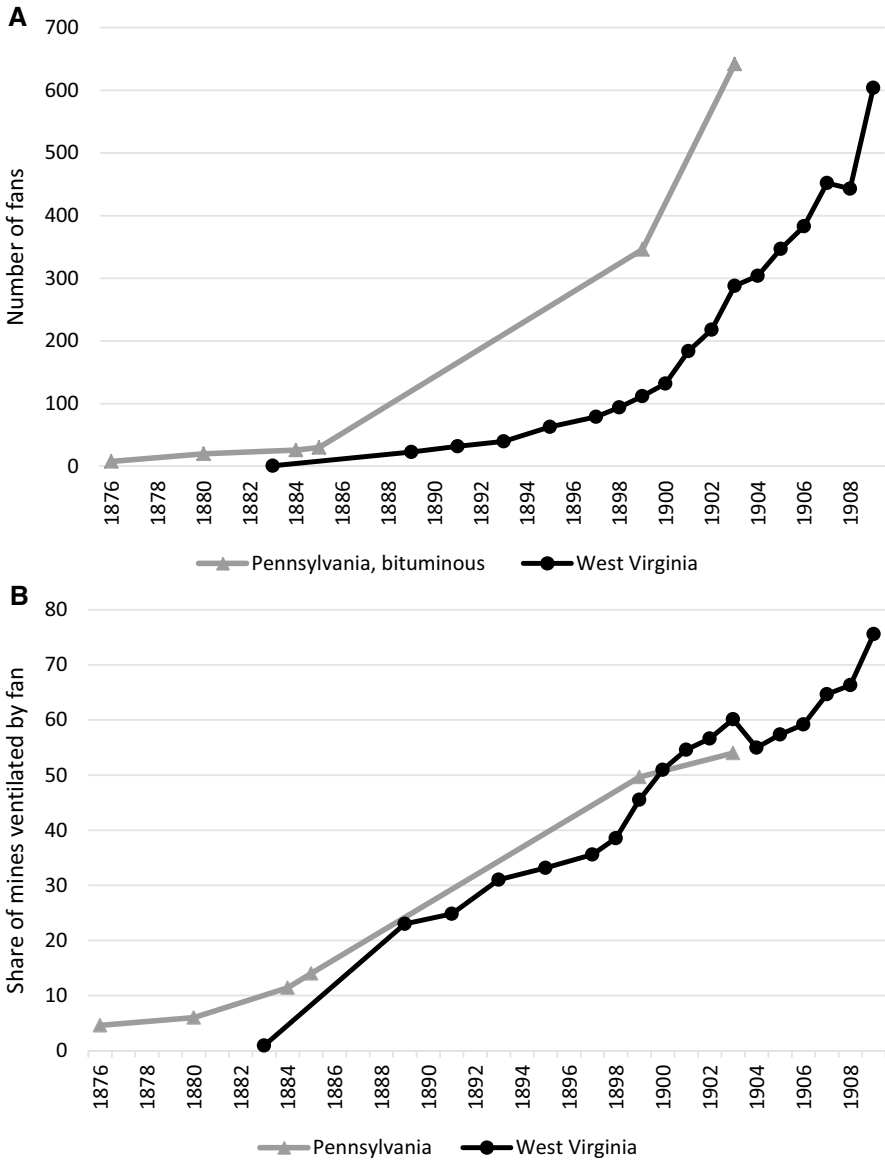
Costs are expressed in 1908 dollars using Edvinsson, <http://www.historicalstatistics.org>



**Fig. 3** Most common methods of ventilation, A. Furnace, B. Mechanical ventilator (Guibal design)  
*Notes:* Figure A.1.B. View from side. Rather than a set of rotary blades, centrifugal fans typically fixed blades onto a cylinder, which spun so as to direct the air flow across the axis of the cylinder rather than parallel to it. Unlike a waterwheel, in which the fluid rotates the wheel to generate power, in centrifugal fans the power source rotates the wheel to push the fluid (air) along. *Sources:* Wabner (1902, plates IX and XVIII)



**Fig. 4** Production and workers in the West Virginia coal basin, 1863–1933, *Notes:* Production and workers available from 1863 and 1880 onward, respectively. *Sources:* See Fig. 1



**Fig. 5** Numbers of fans in major bituminous coalfields: Pennsylvania and West Virginia, A. Absolute numbers, B. Relative numbers, *Notes:* Years used are those where complete information for both coal basins is available. *Sources:* Pennsylvania Department of Internal Affairs (1876, 1880, 1884, 1885); Pennsylvania Secretary of Internal Affairs (1889, 1903); WVDM (1883, 1889, 1891, 1893, 1895, 1897–1909)

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