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As a result of the COVID-19 pandemic, large numbers of airplanes, trains, and buses were put in storage. About 90% of international flights were canceled [1], including 97% of the flights from the U.S. to China [2]. More than 16,000 passenger airplanes were grounded worldwide [3]. After the "essential service plan" was issued by the Metropolitan Transportation Authority of New York City, the number of daily public transport operations decreased by 25% [4]. Amtrak cut 50% of its operations in early April, including 21 routes with reduced schedules and 7 routes suspended [5], [6].

Personal vehicles were left unused in garages. During March, household vehicle travel across the U.S. declined by 70% [7]. There was a 60% reduction of commuter parking activities and a 95% reduction of visitor parking lot usage [8], suggesting that an almost equivalent number of cars were not being used.

World industrial production fell about 5.4% in March, including a 27.2% decline in automotive part production in the U.S., the largest decline in 74 years [9], [10]. Most manufacturers listed as non-essential services zeroed their operation rates. The U.S. benchmark price for crude oil fell to below zero in mid-April [11]. Oil storage facilities were saturated, and tanker ships full of oil waited in the open sea. As a result, oil refineries had to lower their production [12].

Unfortunately, many factories and transportation systems had not properly planned for the shutdown, in part because they did not know the scale of the shutdown, when the shutdown would end, and what factors would affect their equipment and facilities during the shutdown. Upon restarting, some factories and systems have experienced reliability and safety issues.

In early May, a styrene vapor leak occurred at an LG chemical plant located in southeastern India when the facility was restarted after six weeks of lockdown [13]. At least 11 people died, and hundreds were sickened. The estimated loss was approximately USD 1.8 billion, including the likelihood of permanent facility closure [14]. The exact cause of the incident is being investigated, but the probable cause is associated with improper maintenance and startup procedures [15], [16].

On May 22, an Airbus A320 airplane crashed during its domestic flight in Pakistan, causing 107 casualties. The plane had been grounded for two months due to the lockdown, and it was the second flight after resuming domestic service [17], [18]. According to airline officials, the pilots, who had been grounded for several months, forgot about the needed attention to warnings from the air traffic controllers [19], [20] and proceeded with the landing procedure without lowering the landing gear. As a result, the engines hit the ground and the plane crashed in the course of a subsequent landing attempt.

On July 15, a Boeing 737 airplane suffered an engine shutdown during flight and made an emergency landing in Austin, Texas [40], the latest of four cases of engine shutdown on Boeing 737 airplanes used infrequently during the COVID-19 [41]. Inspectors confirmed that the engine's air valves were more likely to corrode on airplanes

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that were less frequently operated. The corroded air valves can get stuck in the open state during flight, resulting in compressor stalls and an engine shutdown. The federal aviation administration ordered inspections of some 2,000 Boeing 737 airplanes which have operated fewer than 11 times since being returned to service [42].

1. How industries responded to the shutdown

Some companies had strategies in place to ensure the reliability and safety of their facilities and systems during shutdowns. For example, the aviation industry has procedures to maintain aircraft that are grounded and placed in storage.

Most airlines, including Delta, Air France, Southwest, and Ethihad, followed their own regular long-term storage procedure during the COVID-19 shutdown. The airplanes were grounded in the desert to protect the airplanes from humidity that can cause corrosion in sensitive devices [3]. The cockpit windows were covered in tinfoil, and the doors were left open to prevent damage by the heat. Since contaminants could accumulate on the aircraft, maintenance managers continued to wash the surfaces of the planes. Vinyl tape was used to seal off gaps and sensors. The planes were scanned for corrosion every week according to the maintenance manuals [21], and electrical systems were turned on every two weeks for two hours. Cockpit and passenger seats were cleaned. Hydraulics and flight control systems were inspected regularly. The planes were towed every one to two weeks to keep their wheels rotating [22] in order to prevent flat-spotting. Finally, the planes are regularly fueled to ensure the fuel tanks stay lubricated, and engines are turned on every 15 or 30 days.

Other companies chose to reduce their operation rates rather than completely shut down. For example, despite the sharp decline in oil demand, oil refineries kept operation at around 60% of capacity (a minimum rate) [12] since they were concerned about the cost of bringing facilities back into operation. Similarly, most semiconductor industries also kept producing because their facilities need to be continuously fed high-purity materials without any process disturbances in order to maintain the product yield and quality [23]. Even in Wuhan, China, the epicenter of the COVID-19 pandemic, semiconductor supplier YMTC kept operating its production line at a normal level [24].

2. Examples of restarting issues with cars

When a machine is non-operational and subject to environmental conditions when in a static mode, some of its components may degrade faster and reach their end of life sooner than those in an operational state. For example, a car is designed to maintain performance and reliability when used regularly.

As noted with airplanes, parking a vehicle for an extended time leads to uneven loading for each tire. The materials on the loaded side of the tire will be deformed until the load is removed. For a car that has been parked for a period, the tire material may maintain its deformed shape even after the load is removed, which is called as flat-spotting, which can be either temporary or permanent, depending on the time duration the load was applied. Flat-spotting induces shake and shimmy conditions when the car runs again, and such tires should be replaced.

Lubricants protect engine parts from corrosion, reduce friction wear, and dissipate heat. In order to keep parts lubricated, vehicles need to operate. Oil pumps driven by the engine circulate the lubricant to contact surfaces of the bearings, cylinders, cranks, pistons, and camshafts. Oil seals located on the ends of the crankshafts prevent the lubricant from leaking out. If a vehicle is not used for several months, the oil seals may dry out. Dried-out oil seals can cause severe wear to the shaft when the engine is restarted [31], and can lead to oil seal cracks.

A thin layer of rust forms on the surface of brake disks when a car is parked for a few days. In general use condition, such rust formation is removed as the driver uses the brakes. However, for a car parked for several months, the rust can accumulate and thicken, resulting in poor contact between the disk rotor and brake pad. This in turn can lead to vibrations known as brake judder, and ultimately a loss of braking ability [27].

Finally, when a car is turned off, many of the electronic devices in the car, such as GPS systems, proximity sensors, anti-theft systems, and smart-key systems continue to operate and consume battery power [28], [29]. A battery

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also loses its charge via spontaneous electrochemical reactions. After a few months, the battery can be completely drained.

3. Human factors

The COVID-19 pandemic has deterred regular maintenance and restarting due to concerns about worker health. For example, several oil companies, including Neste in Finland, Burgondi in Italy, and Lukoil in Russia, delayed scheduled maintenance, fearing disease transmission between maintenance workers [32]. Since crude oil and natural gas contain various corrosive impurities, including hydrogen sulfide, the facilities can be damaged if there is no preventive maintenance and cleaning [33].

Some factories that had resumed manufacturing had to close again as their workers became infected. For example, one of the Tysons Foods factories halted its operation twice in a week because of worker infections [34]. Ford closed and reopened its assembly lines twice within a day [35]. Such frequent closures and resumptions make it difficult for manufacturers to conduct proper maintenance and start-up operations.

About 20% to 50% of all equipment failures are caused by human errors [36]. Although many companies have conducted equipment maintenance during the shutdown period, operators for the equipment are inactive and may lose their proficiency without continuous operating routines. For example, if workers in assembly lines become less proficient, they can use incorrect parts or tools, omit parts, make improper connections, and mishandle equipment [37]. Such errors can result in equipment failures and expose the workers to danger.

For the aviation industry, downtime affects not only the aircraft but also the pilots, who need frequent training and continuous flight experience. For example, U.S. federal regulations, 14 CFR 61.57, state that pilots should make at least three takeoffs and three landings within the preceding 90 days to act as a pilot in command of an aircraft carrying passengers. Certified simulators can keep pilots' airplane control proficiency sharp and their license valid, but the number of available simulators is insufficient to respond to this unique situation where more than 290,000 active pilots are grounded indefinitely [38], [39].

4. Summary

The COVID-19 pandemic has forced many facilities to shut their operations down and idle various pieces of equipment for months. The impact of the shutdown on equipment reliability has varied depending on the preparedness of each industry and company. While some companies have continued to maintain their idle equipment, other companies have delayed a proper maintenance response due to a lack of information when shutdowns will end and concerns over infection among maintenance workers. Upon restarting, companies and individuals must assess their own abilities to operate the equipment they use, as well as the equipment itself.

As the COVID-19 pandemic enters the recovery period, industries and societies are attempting to resume operations. However, such a global shutdown can be triggered again at any time by another pandemic crisis, massive natural disasters, or trade wars. Given the current situation, it is recommended to establish a preparedness plan that can keep equipment reliability during an unexpected shutdown. The preparedness plan should cover not only the maintenance and operation plan for equipment, but also the proficiency of operators.

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