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DETERMINATION OF THE IMPACT OF DISRUPTIONS IN GROUND HANDLING ON AIRCRAFT FUEL CONSUMPTION

Summary. The authors of the paper distinguished two basic problems that occur during the ground handling of aircraft. The first one concerns the identification of disruptions during ground handling that have an impact on the scheduled completion of ground handling. The second problem is determining how these disturbances affect the environment by estimating the increased fuel consumption of the aircraft. In the first step, a catalog of disruptions in the ground handling process of the aircraft, which delays the performance of subsequent aircraft operations, was developed. Simio software was used to analyze the impact of disturbances on the performance of ground service, in which random disturbances were simulated. The simulation was run for several variants, taking into account the sample aircraft and various airlines. The developed model allows for the analysis of the impact of disturbances on the punctual performance of the ground service of the aircraft for various variants with given probability values. In the next step, simulations were performed to determine the impact of the disturbances on the increase in fuel consumption by the aircraft. Research has shown that even minor disruptions increase an aircraft's fuel consumption over a 200-km flight path. The analyzes carried out in this work are of great importance for sales agents and airlines who strive to minimize the duration of elementary activities and eliminate threats during ground handling. Additionally, it is important from the point of view of environmental protection. As research has shown, even small disturbances can substantially increase fuel consumption, which is not beneficial for airlines. Past research has focused on the analysis of fuel consumption by aircraft and emissions during takeoff and landing operations and taxiing aircraft. There is a large correlation between the disturbances occurring at the parking place and increased fuel consumption, which is important from an economic and environmental point of view.

1. INTRODUCTION

Ground handling consists of numerous activities that are managed by many different pieces of equipment and people. This can cause disruptions in aircraft handling for a variety of reasons, which, in turn, can lead to delays in handling, generating a global delay in the scheduled execution of takeoff operations [8]. A report by Eurocontrol [2] indicates that there were long delays in 2018, though measures taken by carriers helped to reduce delays in 2019. The average departure delay increased by 1.6 minutes and was 13.1 minutes in 2018, while the average arrival delay dropped by 1.6 minutes to 12.2 minutes in 2019. The report divides the causes of delays into two groups: reactionary (knock-on)

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and primary. Reactionary delays are the main causes of delays (contributing 5.7 minutes to the average delay per flight). These are the result of transferring a delay—for example, from the departure airport to the arrival airport. The second major cause of delays is primary delays (3.41 minutes on average). This category includes delays related to passenger and baggage handling, ramp or aircraft handling, and delays related to damage to aircraft and ground equipment. Long delays (over 60 minutes) affected only 5.3% of flights (this is an increase from 4% in 2017). These delays do not always occur at busy airports. This may be an indication of incompetent management or under-resourced aircraft servicing equipment. Therefore, it is important that research into ground handling processes leads to increased efficiency in ground handling and minimizes aircraft delays.

In the literature, a lot of attention has been paid to passenger handling at the terminal and during boarding [12]. In cases involving large aircraft, passenger boarding can take longer than other activities such as refueling or cabin service. The processes associated with passenger handling begin at the terminal and may involve less onerous disruptions than aircraft handling itself. Previous research [14] focused on three ground handling activities: boarding, baggage loading, and cabin cleaning. The authors [12] focused on scheduling de-icing operations, resulting in reduced aircraft waiting times and, thus, reduced delays in takeoff operations. Another study [13] presented a model for the optimal planning of aircraft pushback operations. The solution presented cut vehicle travel time by 30% and reduced delays.

In the literature, there is a large number of publications related to ground handling analyzed as a holistic process. The authors of one paper [11] analyzed the procedure of ground handling by checking whether the introduced automation of selected processes involving people reduced delays and costs associated with employed personnel. The originators claim that this will reduce the number of disruptions and even the number of aircraft incidents. Disruptions can occur in a variety of places, and their causes can vary. They can also have a significant impact on the environment. When an aircraft is being prepared for pushback, its engine is started, usually several minutes in advance, and left idle. Disruptions in ground handling may cause the aircraft to idle for longer than planned, thus consuming fuel and emitting harmful substances into the environment. An interesting study [255] investigated the improvement of ground handling operations. The authors highlighted the importance of ground handling costs and identified a method for systematically evaluating cost contributions. The article provides recommendations for reducing ground handling costs by 3.5%. In other research [244, 26], the authors analyzed ground handling, and it was mentioned that an improvement in this area is important for reducing costs and increasing aircraft utilization. The taxiing system was analyzed to obtain reduction time and lower fuel consumption. Analyses of system taxiing have been carried out to estimate fuel consumption and emissions under different taxiing modes. The results showed that a new method for calculating taxiing is optimal in terms of fuel consumption and emissions [22].

This paper examined the ground handling process to identify potential disruptions in this process. Simio software was used to build a model of ground handling while taking potential disruptions into account and to estimate their impact on the execution of the whole handling process. The activities with the greatest impact on process timeliness were identified. As part of the simulation, the impact of random disruptions on the time taken to perform individual activities and on the total aircraft ground handling time was considered. The possible impact of disruptions on the critical paths of the aircraft handling process was also examined.

2. DISRUPTIONS IN THE AIRCRAFT GROUND HANDLING PROCESS

The execution of airport handling processes must ensure the safe preparation of aircraft during all stages of air traffic handling. In addition, it is important to ensure the regularity and continuity of processes at the airport. The most important process and performance indicators in ground handling include:

- ensuring punctuality
- minimizing the use of resources (personnel, GSE Ground Support Equipment)

- avoiding damage to equipment and aircraft
- avoiding accidents involving personnel [11]

The role of the handling agent is to conduct its business in a manner that ensures proper operation and elimination of disruptions at the airport within the scope of its license [13]. Ground handling refers to all services provided to airport users at airports [1]. The time it takes to perform these activities—and the complexity thereof—depends on the type of aircraft and air carrier (this may be due to air carrier standards and policies). Each aircraft type has predetermined steps and estimated times for their completion, as well as a unique GSE layout and connection scheme. Smaller aircraft generally have shorter handling times. In smaller aircraft, some steps may be omitted (e.g., stairs due to the construction of the aircraft). Aircraft ground handling entities try to minimize turnaround times by performing activities such as refueling and passenger boarding in parallel. This shortens the critical path of ground handling [3]. The duration of ground handling depends on the available human and GSE resources at a given airport, meteorological conditions, and the proper coordination of activities. A turnaround coordinator is responsible for coordinating the activities to ensure that they are in line with regulations and agreements between entities, for communicating with other entities, as well as anticipating and responding to disruptions and threats. A massive fleet of ground vehicles performing specific tasks is used during aircraft ground handling. The coordination of operations and the exchange of information between various entities and services involve constant adjustments to the schedule of operations. By estimating runway occupancy times, services can inform each other and ground handlers of available airport slots. The freed-up runway can be used by another aircraft, which, thanks to such coordination, can taxi and take off earlier than planned. Furthermore, by providing real-time information, aircraft ground handling can begin earlier in some cases. Coordination in ground handling and runway operations can increase airport capacity by up to 30%.

The mutual cooperation of services during ground handling can reduce the negative effects of some types of disruptions characterized by randomness. Disruptions may occur prior to the commencement of handling (at the system entrance) [13]; such disruptions are independent of the handling agent. On the other hand, these delays may be dependent on handling agents that have been transferred from the departure airport, including [9]:

- aircraft arrival delay
- runway or taxiway incursion
- blocking the entrance to the stand
- unauthorized trespassing onto the stand
- foreign object debris (FOD) on the stand
- poor and adverse weather conditions

Another type of disruption is those associated with centralized equipment and infrastructure used during ground handling. Each device is characterized by certain reliability indicators, including mean time between failures (MTBF) or its inverse (i.e., the intensity of failures). Each device has a specific MTBF, or probability of failure, while not representing the lifespan of the device. Reliability disruptions affect all sorts of equipment used during ground handling:

- passenger boarding and deboarding equipment (stairs or bridge)
- power generators
- fixed power supply points
- communications equipment
- unit load devices (ULD)
- belt loaders
- catering
- air conditioning service vehicle
- lavatory service vehicle and equipment
- aircraft de- or anti-icing vehicle and equipment
- air start units (ASU)
- pushback tugs
- tanker trucks
- central fuel distribution system

Another type of disruption that occurs during handling is caused by the human factor, which is one of the weaker links in the process. Individuals responsible for performing specific operations may generate disruptions by incorrectly performing activities, improperly using equipment, or failing to comply with applicable regulations and recommendations. The following disruptions can also be generated by the crew of the aircraft being handled:

- unintentional or intentional damage to infrastructure and equipment
- blocking the stand with a vehicle or GSE
- vehicle collisions
- placing vehicles or equipment in the wrong place
- poor securing of equipment and loads, including hazardous cargo
- no blocking of the service road and taxiway during aircraft pushback
- problems during passenger boarding and deboarding
- improper load distribution in the aircraft
- using a GPU without a bridge
- refueling with passengers on board without firefighters' assistance
- problems with lost baggage
- use of equipment by personnel contrary to regulations and recommendations without causing damage to the aircraft
- improper use of equipment or vehicles resulting in damage to the aircraft
- improper use of equipment resulting in accidents during handling
- aircraft crew mistakes (e.g., movement of the aircraft with personnel present underneath, release of the brake after obtaining authorization to proceed to handling)

Additionally, disruptions related to shortages of GSE due to a large number of simultaneous ground handling processes or equipment failures can be distinguished. Such a phenomenon may involve:

- passenger deboarding or boarding stairs
- power generators
- unit load devices (ULD)
- belt loaders
- catering vehicle
- water vehicle
- air conditioning service vehicle
- lavatory service vehicle and equipment
- aircraft de- or anti-icing vehicle and equipment
- Air start units (ASU)
- pushback tugs
- tanker trucks

The possible disruptions described above were assigned to the processes during which they can occur (Fig. 1).

The impacts of the listed events on the punctuality of ground handling performance vary dramatically. Some of the listed conflicts, such as misaligned GSE, can be resolved in a short time without causing significant delays. Human errors, however, often lead to serious problems that prevent aircraft handling (e.g., improper stair or bridge placement), which can cause damage to the aircraft skin, thus excluding the aircraft from further service. The impact of disruptions associated with random damage to the GSE depends on the size and type of damage, which may translate into the availability of this equipment. Disruptions occurring before the commencement of handling result in a delay in the commencement of ground handling of the aircraft involved.

3. GROUND HANDLING MODEL INCLUDING DISTURBANCES

The ground handling model used in the present study was developed using Simio software. Real operation data containing the times of performance of individual activities during ground handling (i.e., the start and end of the activity during the actual ground handling of aircraft at the airport) were used. These were obtained from several low-cost air carriers. Measurements were taken for approximately 80 different flights and divided proportionally for each air carrier and four aircraft types: Boeing 737-300 and 737-700 and Airbus A319 and A320. In the case of low-cost carriers, the passenger and crew boarding and deboarding operations are, in most cases, carried out using stairs, not a passenger boarding bridge. The following operation duration data were used (for each aircraft model) to create the appropriate database for the model simulation:

- securing the aircraft;
- passenger deboarding;
- aircraft unloading;
- refueling;
- water and lavatory system servicing;
- catering services;
- cabin services (cleaning and stock replenishing);
- aircraft loading;
- passenger boarding;
- the start and end of the above-mentioned operations.

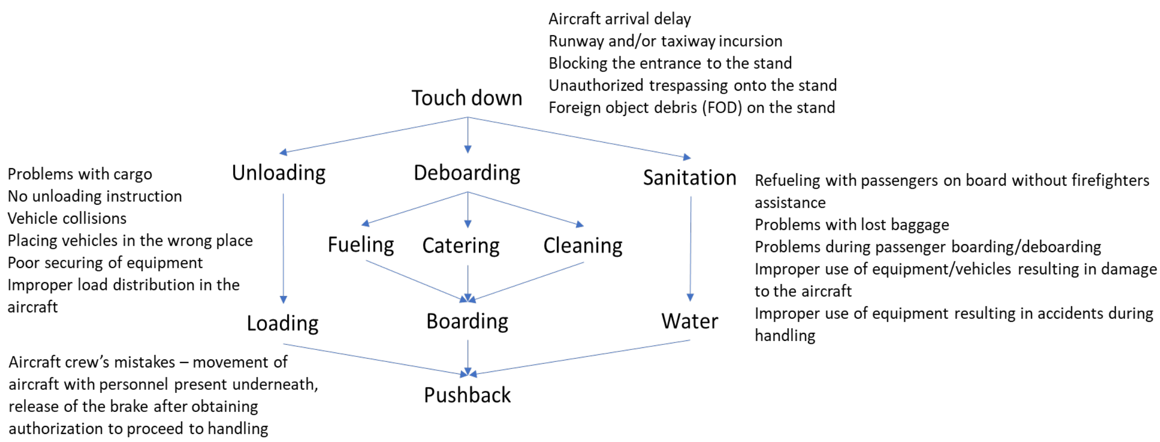

Fig. 1. Ground handling diagram with identified disruptions [own study]

Thus, the developed model reflects the operations performed during the aircraft parking based on the scheme typical for low-cost carriers (Fig. 1). The model does not take into account the operations related to, for example, de-icing the aircraft because it is of a seasonal nature; moreover, it is often performed at another, specially adapted parking stand. Fig. 2 presents the model developed in Simio.

The model simulated the disruptions that can occur during ground handling. Add-on processes were created to simulate the occurrence of random disruptions at various stages of aircraft ground handling. Fifteen different disruptions related collectively to handling errors, waiting for the vehicle to be released, and delayed commencement of aircraft handling were created. In addition, eight disruptions regarding the operation of the equipment were assumed. Major disruptions that would cause a complete cessation of ground handling or the withdrawal of the aircraft from service were not included in the model. The disruptions in Simio were based on decision blocks in combination with delay blocks.

The simulation was performed in four variants that differed based on the given probability. The basic variant is the simplest variant of the model and refers to ground handling during which unassisted refueling is performed (i.e., after passenger deboarding). The second variant (the AC variant) focuses on the types of aircraft being handled. The generated units were split between Airbus and Boeing manufacturers. The third variant (the airline variant) emphasizes individual carriers (the paper presents average results). Similar to the AC variant, there is a breakdown based on the type of fueling. The fourth variant (the random variant) is a modification of the airline variant. The difference is in how the units are generated. In the previous variants, they are generated according to the created flight schedule. This fourth variant does not use a schedule but instead generates flights at random, and the time between flights is generated by a pseudo-random number generator.

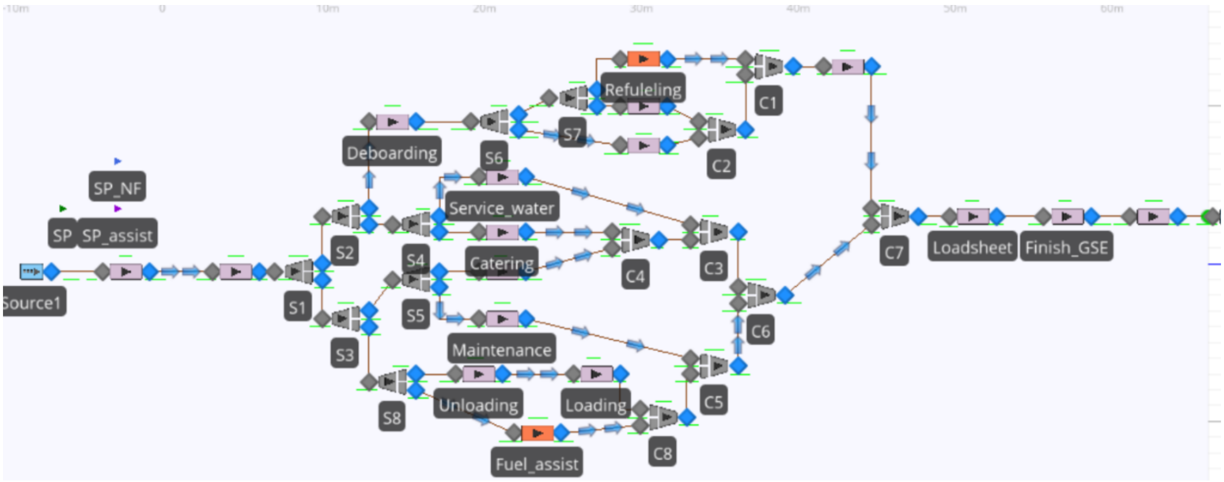

Fig. 2. Ground handling model developed in Simio [own study]

The variants differ regarding their probability of the occurrence of a given disruption during the aircraft ground handling operations. The assumed probabilities were derived from handling agents' incident reports and can be modified or assumed randomly. The following assumptions were made for the simulation: for the basic, AC, and airline variants, 200 aircraft were handled with units being generated according to the schedule. Meanwhile, for the random variant, a random number of handled aircraft was assumed, and units were generated according to the normal distribution. The assumed probabilities of disruptions in each scenario ranged from 0.05 to 0.25. For the last scenario, the probabilities of disruptions were set randomly.

4. RESULTS OF SIMULATION OF THE MODEL WITH DISRUPTIONS

A simulation was performed for the assumed scenarios. Table 1 presents selected results from all simulation scenarios for the basic and random variants.

For scenario one, in which the probabilities of disruptions during passenger boarding and deboarding activities were increased, the average boarding and deboarding time increased by about one minute. Similar situations occurred in the other scenarios. In the last scenario, a significant increase in the times taken to perform the activities was observed. In this scenario, each activity had a high probability of disruption.

Similar calculations were performed for the other variants (e.g., AC), in which the results were split into groups depending on the aircraft model (Airbus and Boeing), as well as by the airline and randomly. For the random variant, the parameters for unit generation were the same as in Scenario 1; that is, the mean was 1 h, and the standard deviation was 0.25 h.

The last test performed was to check how the applied disturbances modify the distribution of critical paths (Table 2). Six scenarios were considered as in previous simulations.

A noticeable effect of the disruptions applied to the critical paths was observed. In Scenarios 1 and 4, boarding, deboarding, and unassisted refueling activities were extended by increasing the probability of the disruption's occurrence during the aforementioned activities. For this reason, an increase in the share of the deboarding-handling-boarding path was recorded. In Scenarios 2 and 5, the probability of disruptions during loading and unloading was increased, which translated to an increase of several percentage points in the share of the path specifically related to loading and unloading. An analogous response occurred in Scenario 3, with the only difference being that it involved a path related to maintenance and refueling.

Table 1
Summary of the simulation results of basic and random variants with actual measurements [min]

Activity	Ave. duration	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6
Securing the aircraft	00:28.5	01:30.6	01:30.6	01:24.6	01:30.0	01:30.6	01:33.0
Passenger deboarding	04:16.2	05:12.6	04:28.2	04:24:0	04:23.4	04:27.0	05:12.6
Aircraft unloading	07:00.0	07:10.8	08:14.4	07:09.6	07:05.4	09:01.2	08:48.0
Refueling	10:04.8	10:36.6	10:12.6	10:09.0	10:46.2	10:46.2	10:54.6
Maintenance	04:30.0	04:40.8	04:37.8	05:48.6	04:35.4	04:40.8	06:00.6
Catering replenishment	05:11.4	05:19.2	05:18.6	06:14.4	05:16.2	05:13.8	06:35.4
Lavatory servicing	07:02.9	07:10.2	07:06.0	08:04.2	07:15.0	07:13.2	08:35.4
Water system servicing	06:15.5	06:27.6	06:28.2	07:34.8	06:27.6	06:22.8	07:57.0
Cabin cleaning	07:02.7	07:21.6	07:06.6	07:48.6	07:16.2	07:21.6	07:40.2
Cabin stock replenishment	03:51.3	03:59.4	03:53.4	03:55.8	03:54.0	03:54.6	03:55.8
Passenger boarding	05:40.0	06:43.2	05:44.4	05:50.4	06:00.0	05:48.6	06:51.0
Aircraft loading	10:30.8	10:28.8	11:46.2	10:33.6	10:48.0	12:32.4	12:01.8
Average aircraft handling time	36:59.2	42:51.0	43:00.0	42:18.6	42:07.9	43:23.4	47:37.8
Maximum aircraft handling time	66:00.0	81:24.0	80:00.0	78:36.0	81:00.0	81:12.0	83:00.0
Minimum aircraft handling time	24:00.0	23:00.0	23:24.0	23:36.0	22:12.0	25:24.0	25:36.0

Table 2
Critical paths for simulation scenarios

Critical path	No disruptions	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6
Deboarding-cabin services- boarding-pushback	70%	76%	59%	71%	71%	63%	59%
Unloading-loading-pushback	36%	28%	47%	35%	34%	42%	45%
Other operations (assisted refueling, maintenance, etc.)	11%	15%	8%	23%	15%	12%	15%

5. ANALYSIS OF THE RESULTS AND EVALUATION OF THE AIRCRAFT HANDLING PROCESS

The applied disruptions were recorded in the increase in the value of the average times taken to perform the activities. Disruptions affecting critical path activities resulted in increased aircraft handling time. The proposed model can be compared to an airport with only one parking stand. The next aircraft can park only when the ground handling of the previous one is completed. In reality, there are far more parking stands at airports. In most cases, the aircraft would be assigned to a different stand. In addition, extending the model to include processes simulating disruptions makes it possible to simulate waiting times or disruptions that occur before ground handling and other disruptions that occur while handling

The critical path analysis revealed that the most common critical path is the one characterized by the sequence of the activities associated with passenger services, cabin services, or refueling (the deboarding – cabin service/refueling – boarding path). The path concerning unloading and loading occurs for about 33% of the measurements. The generalized path for the operations that can be started independently of passenger deboarding was critical for only about 10% of the results.

The impact of the disruptions applied to the path related to passenger boarding/deboarding was not always the greatest. This is due to the randomness of the simulations performed. The scenarios presented earlier assume an increase in the probability of disruptions in the relevant activities while maintaining lower values for the probability of disruptions in the other activities. The dominance of the critical path associated with passenger and cabin services stems from the aircraft type. Ground handling agents and air carriers, especially low-cost carriers, strive to minimize the previously mentioned critical paths. A visible example of shortening the critical path is the removal of refueling from the passenger deboarding – cabin services or refueling – passenger boarding sequence. Doing this provides firefighter assistance during refueling. An examination of the critical paths shows that the disruptions applied—which, in most cases, reached a value of several minutes—changed the distribution of the critical paths.

6. ENVIRONMENTAL IMPACT

Aviation has a significant impact on environmental pollution. A report in the TERM series by the European Environment Agency points to the need for action to minimize air pollution. The report [3] highlights the importance of air emissions. For each of the transport sectors, it determined a share of about 13% of the total greenhouse gas (GHG) emissions from transport in the European Union. It also points out that in the case of air transport, GHG emissions have doubled since 1990. GHG emissions were 25% higher in 2015 than in 2000, and this upward trend continues at a rate of 2% per year.

Aviation emissions result from the combustion of the fuel used for propulsion, and their level depends on the quality of the fuel and the combustion process. High temperatures during fuel combustion promote the oxidation of nitrogen in the air, as well as other reactions with other exhaust components. This results in the formation of nitrogen oxides, which contribute to the creation of ozone and photochemical smog. Most pollutants are introduced into the environment by the power units of passenger and transport aircraft that have the most power and that consume the most fuel in proportion to the value of the generated thrust [15]. Toxic compounds are mainly generated in the upper layers (i.e., at altitudes of 8-12 km above sea level), where long-haul flights take place [16]. Approximately 5-10% of the global aviation fuel consumption occurs at altitudes of less than 1 km [17].

The unfavorable situation and increased emissions occur during the transient operation of internal combustion engines, and this applies mainly to the area around the airport where takeoff and landing procedures are performed. During takeoff operations, the engine is typically loaded at 100% for about 40 seconds; during landing, it is used at 30% of the rated load for four minutes [4]. During ground operations, the engine is subject to the highest loads in order to check, among other things, valve operation and the tightness of oil and fuel systems.

Analyses performed at Heathrow Airport indicated that the activation of the engine check procedure and the emission of harmful substances during ground operations generated about 3% of harmful substances. Takeoff and landing operations contributed to more than 97% of the airport's annual emissions [18]. Emissions of harmful substances were significantly higher during takeoffs than landings due to the higher aircraft engine emission rates during takeoff and climbing. Hence, high levels of emissions affect not only the higher troposphere zones but also the airports themselves and local residents.

Airports are important communication and transportation centers where emissions from various sources are high and can reach up to 60% of total emissions from the airport area and its surroundings [19]. Therefore, it is important to assess the impact of air transport on the environment and to take measures to reduce the negative impact by means of technological, legislative, and operational solutions. Estimating transport activities' environmental impact is possible through a detailed analysis of the generation of emissions during various phases of the aircraft operation, from tarmac operations to the execution of landing operations at the destination airport.

The current research focused on ground handling; therefore, further analysis will concern the activities taking place on the apron and the potential impact of disruptions on fuel consumption. Takeoff operations can be divided into individual stages that differ in terms of the duration and thrust value of the operating engines. In the case of takeoffs, the first stage is starting the engines, which takes place at a contact gate (at the airport terminal) or remote gate before the aircraft's pushback to the taxiway. Ground operations may account for 5% to 40% of the total block time. In each of these stages, the engine load depends on the range of power developed and the operating time. Table 3 shows the thrust distribution of the power unit as a function of the stage of airport operations [20]. The range of power developed and operating time determine the emission of harmful substances in the exhaust.

The values of aircraft engine exhaust components can be approximated using mathematical formulas based on engine performance data and the engine run time at a given thrust depending on an altitude and speed of an aircraft. Basic data on the emission of harmful compounds at airports, as well as the methodology for determining emissions, are available in the literature [11, 6]. Using these data, it is possible to determine the emissions of harmful components of aircraft engine exhaust, as presented previously [20].

Table 3

Engine operating ranges during flight operations over time

Operation	Thrust range (%)	Time (min)
Start	100	0.7
Departure from the airport	85	2.2
Approach to landing	30	4.0
Taxiing/idling	7	26

Source: Study based on [4].

The paper was focused on ground operations that affect fuel consumption and the emission of hazardous substances due to emerging disruptions. Aircraft engines are started when ground handling is completed. In situations involving emerging disruptions, the aircraft may have to wait and continue running until authorization for pushback is issued. Of great importance is the preparation of the aircraft for takeoff—that is, the moment of starting the engines. The engines are started after preparation, radio communication with the airport, request for clearance, reading back the clearance, asking for engine start, starting the engine, requesting a taxiing, taxiing clearance, and taxiing. For the Airbus A320 aircraft, the engine (IAE-V2500) warm-up time for takeoff is two to five minutes after startup [21]. The fuel consumption on the ground at idle thrust depends on the outside temperature and other elements. According to the manual of Airbus A320 aircraft with an IAE-2500-V5 engine, it is 400 kg/h (i.e., 6.7 kg/min) on the ground under standard conditions.

The taxiing operation is also important. At most airports, this can be done with one engine on in the case of two-engine aircraft or with two engines on in the case of four-engine aircraft. At larger airports, taxiing times can be as long as 15-20 minutes. Therefore, turning off the engines reduces fuel consumption but can also increase the risk of damage to an engine running at a higher load. Under unfavorable conditions, the thrust required to start or continue taxiing using one engine may be high enough to pose a risk in congested areas such as aprons or the taxiways close to those aprons. Such procedures shall be developed and implemented by the air carrier. The taxiing procedure with one engine off assumes the activation of APU [21]. This unit is used on the ground while the aircraft is parked to supply it with electricity, among other things. The fuel consumption of an APU depends on its type, the type of load selected, and external conditions. For an A320 aircraft, it can vary between 85 kg/h and 125 kg/h [23]. Based on Airbus data [23], fuel consumption can be estimated with different engine configurations for taxiing operations (Table 4).

Table 4

A320's fuel consumption during taxiing operations

Airbus 320	**All engines**	**One engine**	**Engine out – taxi savings**
12 min	138 kg	92 kg	46 kg
1 min	11.5 kg	7.7 kg	3.8 kg

The simulation performed to explore the effect of disruptions on ground handling completion times showed that with disruptions, relatively long delay times were achieved (as shown in Table 5) for six scenarios (mentioned in Table 1) and five variants (described in Section 3). The scenarios were characterized by different probabilities of disturbance (from 0.05 to 0.25). Based on the simulation results (Table 1 shows the average times of elementary activities), Table 5 shows the maximum and minimum delays for the assumed variants. Each scenario assumes different probabilities of disturbances, which made it possible to calculate the fuel consumption resulting from disturbances (Table 6).

Based on this, an estimate of the fuel consumption with the resulting delays due to disruptions was made. Assuming the fuel consumption of an airplane at idle on the ground at 6.7 kg / min and the fuel consumption of the auxiliary APU at 2.1 kg / min, one can very generally estimate how much more the airplane will use during delays. Table 6 shows the increased fuel consumption of the aircraft when the above assumptions are met.

Table 5

Ground handling delay times for different scenarios and configurations

Time [min]	Scenario	1	2	3	4	5	6
Basic	middle	5.33	6.02	5.33	5.15	6.40	10.65
	max	15.40	14.00	12.60	15.00	15.20	17.00
Airbus	middle	5.28	5.27	5.45	5.63	7.88	10.05
	max	6.00	3.80	1.77	10.72	15.38	14.02
Boeing	middle	2.03	10.23	8.70	10.85	12.57	13.65
	max	5.67	6.20	3.20	12.00	6.60	10.40
Airline	middle	5.40	4.95	5.85	4.28	5.83	10.40
	max	20.80	17.90	16.30	17.30	18.30	22.20
Random	middle	6.90	8.83	7.87	7.03	9.65	16.93
	max	23.25	37.25	25.53	26.95	37.72	67.30

Table 6

Excess fuel consumption of the aircraft resulting from disruptions [kg]

Time [min]	Scenario	1		2		3		4		5		6	
		AC	AC+APU	AC	AC+APU	AC	AC+APU	AC	AC+APU	AC	AC+APU	AC	AC+APU
Basic	middle	35.71	46.90	40.33	52.98	35.71	46.90	34.51	45.32	42.88	56.32	71.36	93.72
	max	103.18	135.52	93.80	123.20	84.42	110.88	100.50	132.00	101.84	133.76	113.90	149.6
Airbus	middle	35.38	46.46	35.31	46.38	36.52	47.96	37.72	49.54	52.80	69.34	67.34	88.44
	max	40.20	52.80	25.46	33.44	11.86	15.58	71.82	94.34	103.05	135.34	93.93	123.38
Boeing	middle	13.60	17.86	68.54	90.02	58.29	76.56	72.70	95.48	84.22	110.62	91.46	120.12
	max	37.99	49.90	41.54	54.56	21.44	28.16	80.40	105.60	44.22	58.08	69.68	91.52
Airline	middle	36.18	47.52	33.17	43.56	39.20	51.48	28.68	37.66	39.06	51.30	69.68	91.52
	max	139.36	183.04	119.93	157.52	109.21	143.44	115.91	152.24	122.61	161.04	148.74	195.36
Random	middle	46.23	60.72	59.16	77.70	52.73	69.26	47.10	61.86	64.66	84.92	113.43	148.98
	max	155.78	204.60	249.58	327.80	171.05	224.66	180.57	237.16	252.72	331.94	450.91	592.24

Assuming the fuel consumption on the ground is 800 kg/h [21] (i.e., 13 kg/min), the excess fuel consumption may range from 35 kg (2.6 min) to nearly 600 kg (45 min). The results clearly show that disruptions may cause an increase in fuel. Translating this into cost-effectiveness, which carriers are very concerned about, these are significant financial resources.

7. CONCLUSIONS

Due to the multitude of activities, the involvement of entities (often with conflicting objectives), and the dependence on other services at the airport, ground handling is vulnerable to disruptions. The coordination of individual activities with the entities involved in ground handling and with other services at the airport increases the efficiency and quality of ground handling and other operations.

Ground handling disruptions are largely generated by human errors. Despite the rapid development of autonomous vehicle technology, the requirements for equipment used during ground handling are merciless. Such vehicles would need to operate with high precision (e.g., when connecting the device to the aircraft) and navigate roads so that they do not conflict with other vehicles, objects, or people.

The performed simulation indicated that the change in the probabilities of occurrence of disruptions affects the activities on the critical path and translates into an increase in the time of performing these activities and, consequently, the entire ground handling process. It has been observed that even short disruptions can change the course of critical paths for carriers. For some simulation scenarios, a decrease in the proportion of the dominant path of deboarding-refueling or cleaning-boarding from 70% to 59% was observed while increasing the proportion of the other paths.

Ground handling is a complex process during which several activities are performed simultaneously. The model simulates disruptions occurring before the start of an activity (e.g., connection errors) or disruptions during the activity (e.g., the incorrect protection of a pallet or tanker truck damage). This allows us to verify how a particular disruption affects the performance of an activity and the ground handling process as a whole.

A very general estimation of fuel consumption due to emerging disruptions has been made, which is not a large amount per flight. However, when analyzed globally, it constitutes a significant amount of fuel consumption. Therefore, it is important to eliminate the resulting disruptions, which, as demonstrated in the simulation, can cause significant delays to aircraft operations. Even if a particular part of ground operations has a relatively small impact on fuel consumption, it should not be underestimated. Various initiatives are being implemented to potentially minimize the emission of harmful substances. Developing proper procedures and preparing standards for flight crews and ground personnel is important for reducing fuel consumption.

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