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Planning the natural development of a peripheral vertex on the example of a regional airport in Central Europe

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ABSTRACT

In this paper, a young airport in Central Europe is presented as a peripheral node of a complex network, subject to Luce's natural laws of development. Research conducted since the late 1990s has focused on creating models that apply to the entire network. Even the development of the most important nodes of a complex network, the so-called hubs, is considered as a consequence of the topology of the entire network. The paper considers what laws and models can be applied to a single, peripheral network node, compared to the widely used exponential models. The presented analysis of the dynamics of the scheduled traffic at the Lublin Airport allows for forecasting its further development. Thus, the methods proposed here for the case study of a regional airport enable us to specify a forecast for the further development of any peripheral vertex of a complex network of a transportation system. On the basis of this analysis, it was pointed out, among others, that seasonality expressing the dynamics of a complex network, so far expressed in statistics using the time series method can also be approached in the Elliot waves terminology and used to predict the profitability of a regional airport. It was also established, that since 2015 the regional demand for civil aviation operations in the General Aviation category has been saturated at the Lublin Airport, reaching the level of 1750 operations per year.

Keywords: airports, air transport, peripheral vertex, complex networks, statistical analysis.

INTRODUCTION

The term complex networks refers to graphs characterized by a more complex topology than networks described using random graphs with a specific (predetermined) number of vertices and connections (edges), so-called classical random graphs [1]. The concept of complex networks in its current form began to take shape in the late 1990s with the emergence of the terms small-world networks [2] and scale-free networks [3, 4]. The next year, Dorogovtsev et al. [5] found the exact form of the stationary distribution of the number of incoming links based on the preferential attachment rule given by Barabási and Albert [3]. Since then, the concept of complex networks has been developed and its applications have been found in other areas [6–9].

Dorogovtsev and Mendes [10] described many examples of complex networks in the physical, biological world and in human activities.

They pointed out there are two characteristic features of complex networks: their evolutionary nature (where new edges become attached to vertices preferentially – the popularity is attractive rule) and as a consequence the presence of strongly connected sets of nodes (so-called hubs) which play a key role in these networks. The adoption of such description of network topology means that the vast majority of contemporary networks can be considered to be complex ones. For example, the characteristics and the properties of complex networks can be used to effectively and efficiently describe transport networks [11, 12]. Especially air transport network is characterized by the presence of hubs in the form of major airports.

It should be noted that they characterized networks created by using the classical preferential attachment model (BA model). The networks obtained in this way have the scale-free property and quite short average distances between vertices. The latter are one of the characteristic features of small-world networks. However, the BA model does not achieve the scale-free property in terms of the clustering coefficient, which decreases with the growth of the network, in accordance with the approximated formula (lnα(t))^2/t, for a network with t vertices [13]. Therefore, there are constantly articles modifying classical models, which allow obtaining the sought-after network properties. Examples of such modifications include, for example, a model taking into account geopolitical considerations for an air transport network [14] or a mode or the k2 model, in which new nodes join nodes of the existing network in proportion to the number of nodes one or two steps away from the target node [15–18].

However, until now, the interest of researchers of complex networks, if it referred to the vertices of such a structure, was mainly directed at hubs [3, 10, 19], to a lesser extent at vertices with a high betweenness centrality coefficient (this measure was associated with the stability of the network) [20]. This is obvious due to their importance for the entire graph, but this importance causes drawing attention away from the remaining vertices of the complex network, in particular from those filling the distribution with a heavy tail, as it were, on its other side, with vertices with a small number of connections, let's call them peripheral vertices. And yet it is the peripheral vertices that constitute (quantitatively) the majority. What is more, in theoretical works [3, 4, 10] describing the growth of different types of networks, the emergence and development of vertices is presented as a consequence of the topology of the entire network. Moreover, when describing complex networks, their scale-free nature is assumed, i.e., as a rule, the entire network changes, including the vertices, but its topology does not change. There is a lack of research devoted to individual vertices, especially peripheral ones, and in a complex air transport network:

1. The creation of a new node (airport) involves huge financial and organizational outlays;
2. Peripheral nodes are most at risk of disappearing for economic reasons.

Let us compare this situation to the case of networks such as the complex Internet network. The end of a single node (closing a given website) does not in principle affect the entire network for four reasons:

a) The creation of another node in the network does not generate large costs;
b) The nodes of the network are globally accessible (despite the hierarchical nature of the Internet network, the user - apart from certain exceptions - can use any website worldwide). This in turn causes the subsidiarity of nodes, i.e. the user can easily find a website with a similar topic to the one that has just been closed, which he has used so far;
c) The size of the network (expressed by the total number of nodes in it);
d) The generally high resilience of complex networks. This was already written about by Dorogovstev and Mendez [10], they refer (in chapter 6.3) to the simulation carried out by Albert et al. [21], but there the "attack" on the network was carried out only by simulating the removal of hubs, not peripheral vertices.

It is necessary to mention another property of the vertices of the air transport network, especially the peripheral vertices. Air transport is one of the most expensive forms of travel, both for the passenger and for entities offering flights. Therefore, it is usually not only a private investment, but also a local government investment, and often even includes funds from the state budget or international organizations (such as the EU) [22–24]. However, for the same reasons, it attracts the wealthiest travelers and provides the greatest opportunities due to the distance. Therefore, it is an investment that has a large impact on the development of the region in the direct, indirect, induced and catalytic scope. All this means that local governments often pay extra for airports so that they do not go bankrupt. It should also be noted that the analysis of theoretical works [3, 10] and the actual functioning of the air transport network [25] indicates that the emergence of subsequent vertices statistically generates more traffic for the previously existing vertices, the larger these vertices were. So the biggest benefit is for the hubs. All this means that we can consider each node of the air transport network important.

The above description allows us to define a complex transport network as:

1. Spatial network [25];
2. Scale-free network [25];
3. Hierarchical network;
4. Small world network [25];
5. Network with vertices with local accessibility. Barthelemy [25] places great emphasis on the role of distance in the air transport network, but he rather means the costs between vertices, and the issue of using air transport has two more conditions, i.e. distance from the airport of the place from which one wants to fly and distance from the airport of the place to which one wants to reach;
6. Network with a large impact on the region even of peripheral vertices.

Therefore, this paper focuses on regional airports, which are peripheral nodes of the complex air transport network. It discusses problems related to the coexistence of regional airports with hubs and their operation within the regional, national/international structures. It also presents an outline of the policy that peripheral airports should pursue in order to develop themselves.

METHODOLOGY

This study considers laws and models that can be applied to a single, peripheral node of an air transportation network to forecast development based on the laws of nature captured by the scheme of variant functions already included in the work of Luce [43]. The functioning of these laws can also be observed by developing a case study of regional airports in Central Europe (Lublin Airport). The methods proposed here for the case study of a regional airport allow for determining the forecast of the further development of any peripheral node of a complex network of a transportation system. Our analysis was compared with the time series method previously expressed in statistics, which can also be captured in Elliott wave terminology and used to forecast the profitability of a regional airport. In this case, reference was made to data from regional airports in Spain and Germany. Elliott wave theory uses basic elements such as shape, proportions and time. The use of wave formation is the most important, the next step is to determine its proportions, thanks to which it is possible to determine the range of demand for transport services, and then their relationship in time, which is used to confirm previous data. The adoption of this economic analysis for forecasting transport services is much more precise than previous time series analyses. For this reason, it was considered that the choice of this analysis will be more beneficial for business models of transport networks. The next step of the analysis was to present a forecast that can be used for investment planning for regional airports in comparison to the currently used exponential models.

The following subsections provide detailed descriptions of the individual stages of this analysis for a regional airport in Central Europe.

Complex networks

Transport infrastructure of a complex network connects cities and takes into account human activities combining social, economic and environmental systems with urbanization and population growth. In addition, the transport network contributes to the socio-economic development and improvement of the quality of life by generating an inter-city or a city-centre connections in the urbanization process [26–29].

Networks differ in the distribution of degree vertices defined as the probability distribution P(k). The size of P(k) defines the participation of nodes in the network with the degree k, in other words the probability that a random node will have the degree k.

The research conducted by Barabási and team [3, 4] led to the discovery of a property previously unknown, but commonly occurring in real-world networks: distribution of vertex degrees in real networks has exponential nature:

$$P(k) = C \cdot k^{-\alpha}, \;\; \alpha > 0 \tag{1}$$

In such networks, many nodes have only one edge, at the same time there are nodes with a huge number of edges, so-called hubs. A good example of such a network is the network of air connections - in which there are a small number of large hubs and a lot of poorly networked airports with a small number of connections [6]. Such distributions are referred to as “ fat-tailed distribution”.

Random networks are divided into static networks and evolving networks. Macroscopic characteristics of static networks (number of nodes and connections, clustering coefficient, distribution of vertex degrees) do not depend on time. In the case of networks evolving their characteristics (including the number of nodes and edges, patterns of internodal connections), change over time [30].

Various network implementations result from random connection of vertices, where for a selected vertex a variable sequence of steps most often occurs (k_1, k_2, …, k_n). As some scheduled air connections take place on selected days, therefore, in aviation such sequences can be analysed on a daily, weekly, seasonal or long-term basis.

In real complex networks, the number of edges grows faster than the number of vertices. This is characteristic of air connections. Such networks are called accelerated growth networks. In the most cases, accelerated network growth may be related to the fact that new connections between the old network vertices may be created and other edges, representing relations between vertices, may disappear [6, 7].

The growing strategic importance of research into the structure, reliability of the functioning of complex networks and their resistance to intentional attacks and accidental defects are of huge practical importance. Thanks to such research it is possible not only to forecast further network growth, but also to wisely manage the resources of these systems and formulate procedures for dealing with crisis situations [6, 31].

Barriers to the natural growth of air traffic

Sawicki considers various demographic barriers to the growth of air traffic [32]. Bel and Fageda [33] give examples of instruments which are alternative formulas for servicing unprofitable airports in Anglo-Saxon countries and the ones of the European Union, which guarantee a certain level of traffic. The main motivation for the privatization of Australia's airports was the need to liquidate immense federal public debt. The national fund of 26 major commercial airports subordinate to the Canadian federal government finances investment and operational losses of 69 local and regional Canadian airports. In Spain, larger airports are not profitable and do not finance the smallest ones.

Planning investments in air transport infrastructure should primarily result from purely substantive (market) premises, and in the very least from political reasons. Unfortunately, the example of Spain and selected airports in Central Europe [29, 34, 35], and around the world clearly demonstrates that the latter premises played in many cases the main if not the most important role. Benefits for a given region related to the operation of the airport will only be achieved if real demand for air transport services exists, ensuring an adequate level of air traffic (and, as we know, the demand for air transport is shaped by multiple factors). Otherwise, airport managers will be faced with a fundamental dilemma: proceed against state aid rules and subsidise air carrier connections maintaining current unprofitable airport operations or declare bankruptcy [36–38].

In the case of the Catalan Government (Generalitat de Catalunya) financing Lleida-Alguaire Airport (ILD) for almost € 130 million in Catalonia in 2012, the traffic was present seasonally (to Menorca from July 22 to September 7 operated by Air Europa and twice a week (Fri and Sat) connections operated by Air Nostrum to Palma). However, the airport was supposed to have supported air transport within the western part of the region, Andorra and international connections. Earlier, for less than a year (from April 2010 to March 2011), Ryanair offered regular international flights from ILD to Frankfurt-Hahn and Milan-Bergamo. Airport managers are currently taking all measures to encourage at least charter carriers to operate from the airport. For this purpose, they undertake various types of activities in cooperation with the Catalan Tourist Board and private entrepreneurs from the region. Further examples of unsuccessful and, at the same time, very expensive investments of public funds in aviation in Spain are given by Wasilewski [38]. It is therefore important to ensure that unprofitable regional airports do not impose unnecessary burdens on public finances and distort competition on the internal market. Sustainable growth of airports and airlines requires full compliance with state aid rules and avoiding harmful duplication of airports [39]. Recent research has revealed that out of 48 regional commercial airports built in Spain in the last 20 years only 11 have achieved profitability. There are around 20 airports serving less than 100,000 passengers per year, well below the break-even point of about 500,000 [33, 40].

In the last quoted document on the activities related to the financial crisis in Spain, the European Commission, addressing the problem of unprofitable regional airports, clearly indicates that their functioning is a significant burden on public finances. Thus, investments in the field of airport infrastructure should be implemented only where real potential for air traffic development is present, enabling airports to operate in conditions of market competition. In retrospect it becomes apparent that in many cases in the EU member states decisions on the launch of airports or their dynamization were not supported by reliable financial and economic analyses, taking into account the real market demand for air transport services that would ensure airport profitability in long-term functioning. In this work, selected aspects of mathematical modelling of the growth dynamics of air transport are analysed. With the use of various research tools it allows for identifying some of the wrong moves of management bodies responsible for the development of air transport.

The presented models omit unexpected events (so-called Black Swans), which are rather impossible to predict. Such events often have a huge impact on the world and negatively affect the economy and society [41]. Examples of this phenomenon in recent years include: the global crisis of 2008, the isolation of society due to Covid-19, sanctions caused by the war in Ukraine from 2022. These last two examples directly influenced the need to limit modeling work for the natural development of the airport under consideration (LUZ). The several-year gap caused by these events disrupted the air traffic of this airport so much that only at the end of 2024 did passenger traffic return to the state of 2017. Therefore, further continuation of modeling work on the natural development of the LUZ airport under consideration in time will require the complete removal of the period of 2019–2024 from the considered models as outliers. It will always remain a matter of debate which social and economic processes can be considered natural and which are the consequence of human intervention, understood here in the statistical sense as the value of a separate factor.

Models of the laws of nature

Starting with Weber-Fechner's law, based on the typology of Stevens' measurement scales [42], it is Luce [43], who on the basis of psychophysical research at Harvard University noted that the laws of nature expressing the relationships between two different random variables: independent and dependent can be expressed variants only with power, exponential, logarithmic or linear functions. Such relationships not only have an objective physical character but also a psychological one. Therefore, they have been discovered and observed in various specific domains, e.g. in biology (for both animals and plants) [44, 45]. Further numerous examples of the applicability of these rules in nature are furnished by the world literature [3, 6, 46]. For example, power laws are very common in the natural and social environment. And thus, one of the first documented power laws is the Pareto distribution [47, 48] in relation to income and the Zipf law [49] in relation to the frequency of word use. It becomes apparent that these seemingly distant domains can be described through models created for complex systems such as biological, computer or social ones. Andriani and McKelvey [50] list 141 examples of the existence of power laws in phenomena related to the specificity of organisation and management. The existence of power laws is often a derivative of complexity; in essence, when individuals are dependent and mutually interacting. In the globalising world of air transport, complexity in business is ever growing in size. It results from the fact that companies operate on many markets, which are culturally different, subject to the influence of dispersed shareholders with different interests and various interest groups, for example: investors, employees, clients, legislators, suppliers, competitors, etc. The chain of connections and dependencies, within which the company operates, becomes extremely complicated with proceeding globalisation. The reality is more dynamic, the number of shocks to which the company is exposed increases - all these affect the management strategy, stipulate faster and more resolute reactions [51]. It should not come as a surprise that the world of enterprises is complex and a great number of empirically confirmed power laws function in it, e.g. the size of companies is measured by both the number of employees and the market value [52, 53], bankruptcy [54], remuneration of the CEO (chief executive officer) [55], behaviour of share prices or distribution of income [29, 34, 56].

It is known that airline networks themselves function, develop, modify or go bankrupt, adapting - out of necessity - to the natural laws of psychology, economics, physics, technology, sociology and politics. At the same time it is only the knowledge of these numerous laws that allows one to obtain a variety of benefits therefrom, while the complexity of the network processes taking place there, is simplified by statistical models showing the beauty and power of a dynamic world. In addition to the laws of nature indicated by Luce [43] to analyse the dynamics of the network, sometimes tools can also be used: time series [57, 58], fractal models [59], statistical process control [60–63] or the Elliott waves theory [64–66]. In this way, we can express the constant concern of managers as well as network researchers resulting from ignorance of the future.

A regional airport in Central Europe

Europe has recorded a historic moment when passenger traffic exceeded 2019 levels for the first time since the Covid-19 pandemic. In 2024, European airports will handle over 2.5 billion passengers, up 7.4% compared to 2023 and 1.8% compared to 2019. This growth was mainly driven by the growing number of international passengers (+8.8% compared to 2023), while domestic traffic only grew by 2.5% year-on-year and remains below pre-pandemic levels. Aviation in Europe is currently developing at two speeds – while the overall market has reached 2.5 billion passengers, exceeding 2019 results by 1.8%, the situation in individual countries is diverse. Poland recorded a dynamic increase to 59.5 million passengers, which is 22% more than before the pandemic, but half of European airports have still not returned to pre-crisis levels [67].

Poland is still the fastest growing aviation market in Europe. In 2017, Polish airports serviced 40.1 million passengers, i.e. by 6 million (i.e. +17.7%) more than in the previous year. This means that, statistically, at that time every Pole travelled by plane. However, European leaders are far ahead in this respect - the Norwegians use the aircraft six times a year, and the Germans four times. The Warsaw Chopin Airport is the largest Polish airport remains, which served over 21.3 million travelers in 2024 and thus exceeded the planned capacity limit of 20 million. This is 15.1% more than a year earlier. It is worth noting that this airport is responsible for 36% of all air traffic in Poland. The newly created Central Polish Airport is planned to take over the role of the main transport hub in this part of Europe. This huge hub is supposed to compete with other major airports in Europe.

The share of the regional airports in the air traffic of Poland has been increasing from 31% in 2004 to 64.4% in 2018. During the period of 2007–2013, due to numerous infrastructure investment projects, both at the airports and on access routes to them, the accessibility of airports for the inhabitants of Eastern Poland, especially Lublin and Podlasie provinces, increased significantly. It took place mainly as a result of the opening of new airports in Lublin and Modlin in 2012 [68]. The Lublin Airport joint stock company (IATA code: LUZ, ICAO code: EPLB) is formed by four local government shareholders. The young the Lublin Airport recorded losses of 25 million in 2015. At the same time, it improved the sales result by over 7.5 million [24]. "If we record such a large increase each year, we will become a profitable port in the next four years," said Krzysztof Wójtowicz, president of the airport [69]. But the growth process of many airports was interrupted by the Covid-19 pandemic. The Lublin Airport in Świdnik meets the highest EU requirements and in 2016 the airport obtained the European Certificate for Public-use Airport. This was related to the launch of the ILS system of II category in 2016. Until then, the regional The Lublin Airport was used mainly by carriers performing scheduled air operations (Ryanair, Wizz Air, Eurolot, Lufthansa, BMI, LOT, Easyjet, Bravo Airways) and occasionally charter carriers (Carpatair, Small Planet Airlines, Travel Service lines). The expansion of the passenger terminal at the Lublin Airport, which was divided into stages, is dictated first and foremost by the need to increase the capacity of the Non-Schengen departure hall, which is a consequence of increasing air traffic. This airport also hosts General Aviation traffic – intensive and fairly stabilized since 2015 (Figure 2). In 2016, the work on the construction of the cargo terminal was completed. In the immediate vicinity of the Airport, the base of the Air Rescue Service is being established.

RESULTS AND DISCUSSION

Models of the dynamics and natural development of a complex network of a scheduled air operations

In 2017, at the Lublin Airport, 0.43 million passengers (i.e. +14% increase) were served, which is only 1% of the total passenger traffic of Polish airports. June 2018 is the moment of significant changes in flights from this regional port. Almost simultaneously, Ukrainian airline Bravo Airways are launching connections between Lublin and three cities in Ukraine: Kiev, Kherson and Kharkov.

However, the process of natural development of the Lublin airport was interrupted by Covid-19 and Russia's aggression against Ukraine in February 2022. In 2024, the Lublin airport served nearly 426,000 passengers, which is about 7% more than a year earlier. At the same time, this port served 4.011 aircraft (an increase of 7.5% from 2023) [70]. Thus, in 2024, the airport's traffic only returned to the state of 2017, and that with a changed connection structure. Hence, due to the global crises, it is necessary to completely remove the period of 2019-2024 from the considered statistical models of the airport's natural development. From 2025, LUZ airport will launch connections to Girona, Spain, and Fiumicino near Rome. From April 2025, daily air connections between Lublin and Warsaw will be restored [70]. The longer change process in the flight schedule of this regional airport in Central Europe reflects the dynamics of travel directions shown in Figure 1 and 2.

The linear aspect of the process of opening new directions of services is already evident in Figure 1. In addition, the slope of the regression line in Figure 2 communicates that despite considerable fluctuation of air traffic, from 2012 to 2018 the number of airports connected with the Lublin Airport worldwide has never fallen below 4, and at the same time, on average, at the rate of $\left(0.0038\cdot365\right)^{-1}\approx ¾$ linearly by one. It is suggested here that the knowledge of this linear parameter seems to be essential from the point of view of managing the reliability of this port's development. And thus Figures 1, 4–5 indicate that during this period, for a year staring from spring 2014, there occurred a periodic incorrect adjustment of the number of scheduled services to the actually existing stable upward trend for the number of passengers using the Lublin Airport at that time. It resulted in the gradual liquidation of the majority of newly opened connections, i.e. the deletion of half of the previously planned number of airports connected with Lublin, including all domestic and Italian ones. It is worth noting at this point that Figure 2 indicates the relationship between the date (i.e. an independent variable expressed on the interval scale) and the number of airports connected with the Lublin Airport (i.e. a dependent variable expressed on the absolute scale). Due to the arrangement of the measurement scales resulting from permitted operations on variables, the dependent variable also possesses the properties of the ratio scale and the interval scale [71, 72]. At the same time Luce [43] noted that the only possible relationship between variables on interval scales can be in the form of a linear law. In this figure, it can be noticed that the deviation from

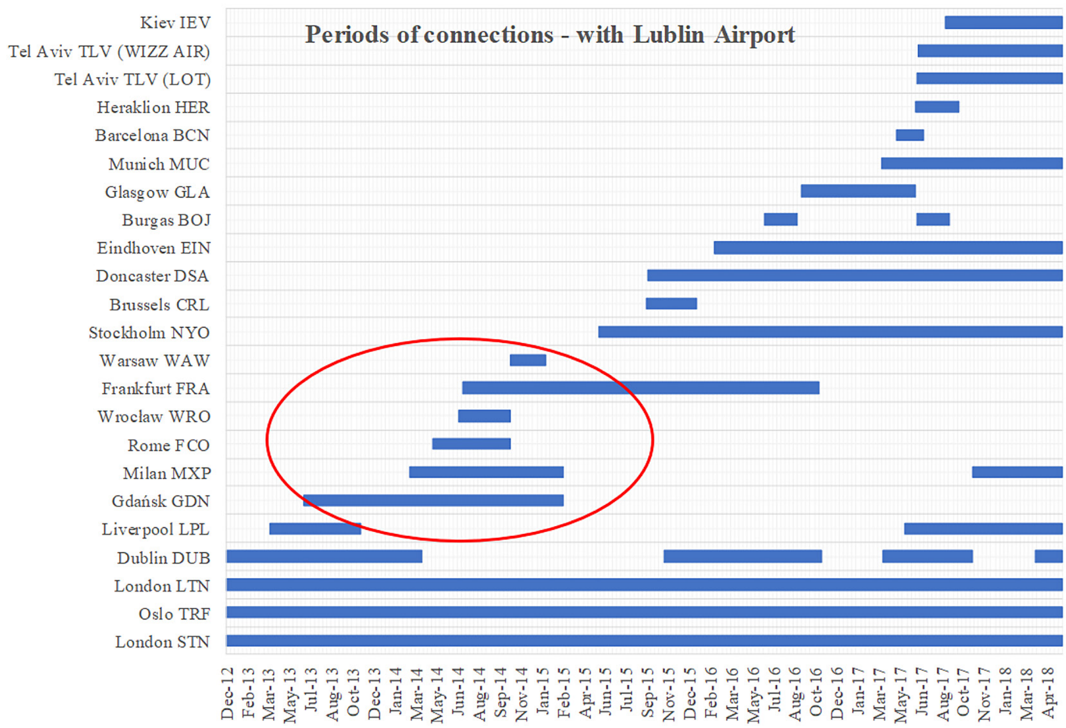

Figure 1. Duration of connections from the Lublin Airport with a highlighted situation of a deep planning crisis

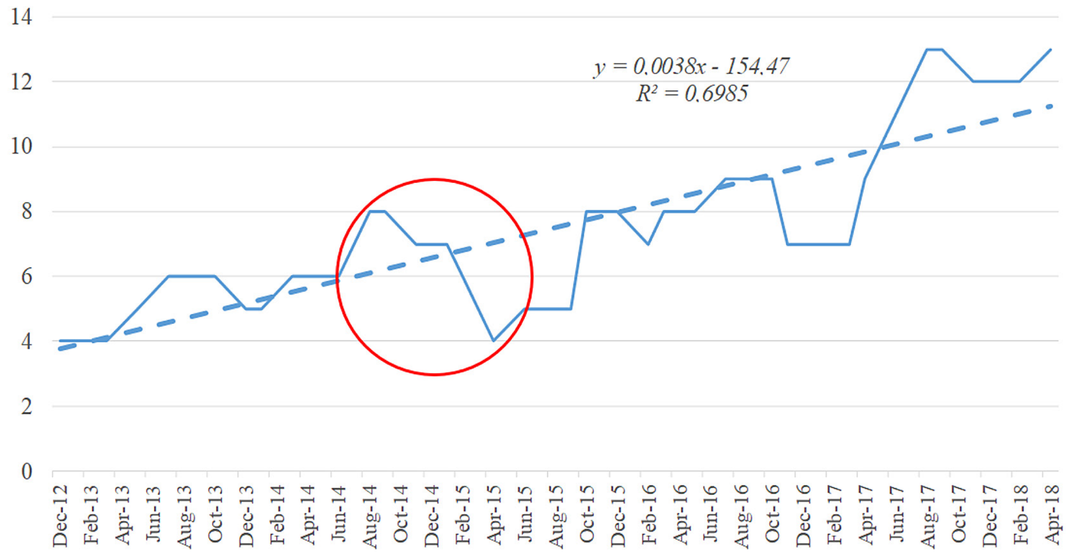

Figure 2. The increase in the number of airports connected with The Lublin Airport in 2012–2018 along with the highlighted situation of deep planning crisis

the initially unknown and unidentified natural development rate of this airport quickly necessitates introduction of organisational adjustments each time. For similar variables in Figure 3, one may notice the effect of additional external factors causing an annual delay in a fairly stable increase in the number of scheduled air operations during the year. The phenomenon observed here confirms the necessity of conducting continuous research on the development of complex air connection networks [6]. It is noted that such a deep planning crisis at this airport has not reoccurred yet, and the simple regression line $y = 131.04 \cdot x$ in Figure 4 reveals that in the remaining period, one scheduled air operation was used by about 131 passengers. At the same time, this relationship expressed by the mentioned simple regression line is a special case of a power function form (first degree) expressing the relationship between the variables appearing here, defined the ratio scales, which Luce postulates with his work [43]. Observations deviating from the regression line in Figure 4 reveal periodic maladjustment of the scheduled traffic to the actual number of passengers.

The traffic at the Lublin Airport in the period between December 2012 – May 2018 is expressed by two courses: the time series of the number of flight operations and the time series of the number of passengers served contains almost linear growth tendencies (trends) and additive components (seasonal fluctuations) and in the form of typical Elliot waves. And thus for the Lublin Airport, a linear relationship between the number of passengers served since t time is initially described. The relationship corresponds to the null hypothesis:

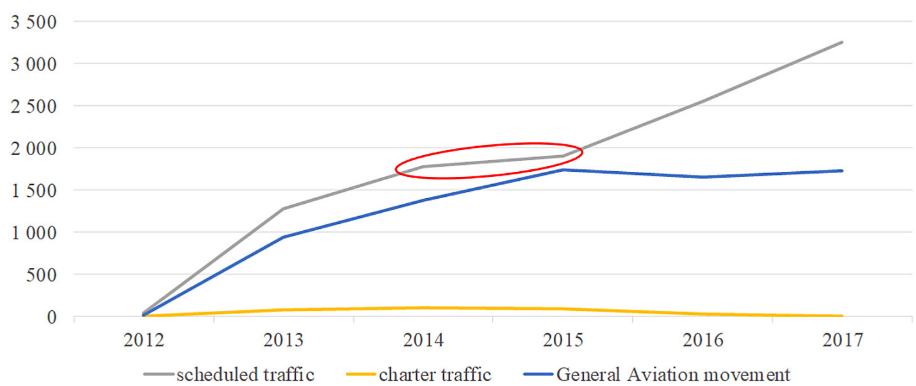

Figure 3. An unstable (delayed by a year) increase in the number of scheduled air operations at the Lublin Airport

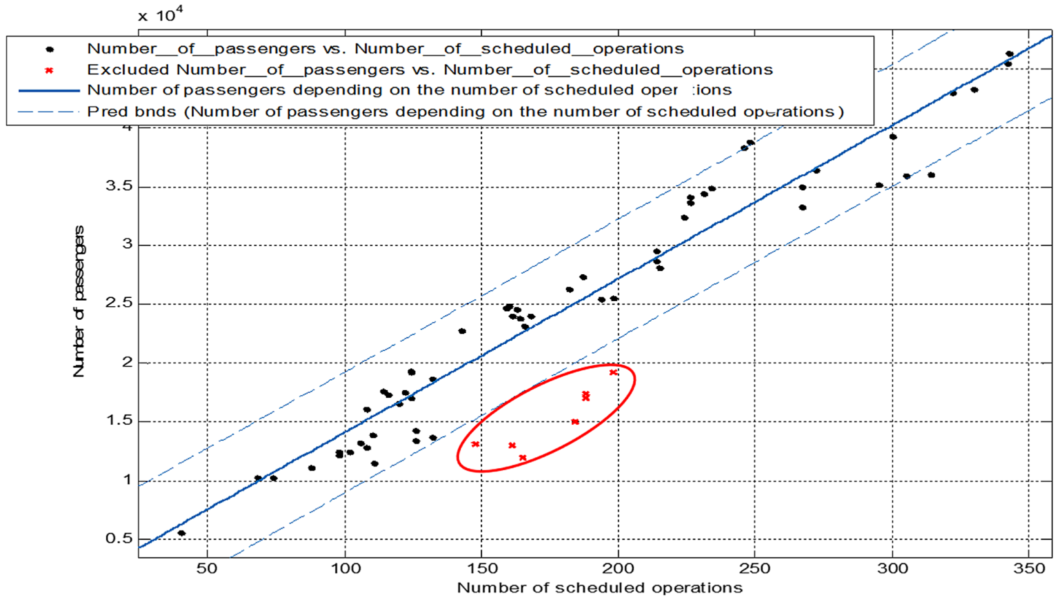

Figure 4. Exclusion of the observations (from the period between July 2014 – January 2015) deviating from the regression line $y = 131.04 \cdot x$ for $R^2 = 0.8772$ beyond 95% of the confidence area allows one to discern periodic maladjustment of the scheduled traffic to the actual number of passengers at the Lublin Airport during the years 2012–2018

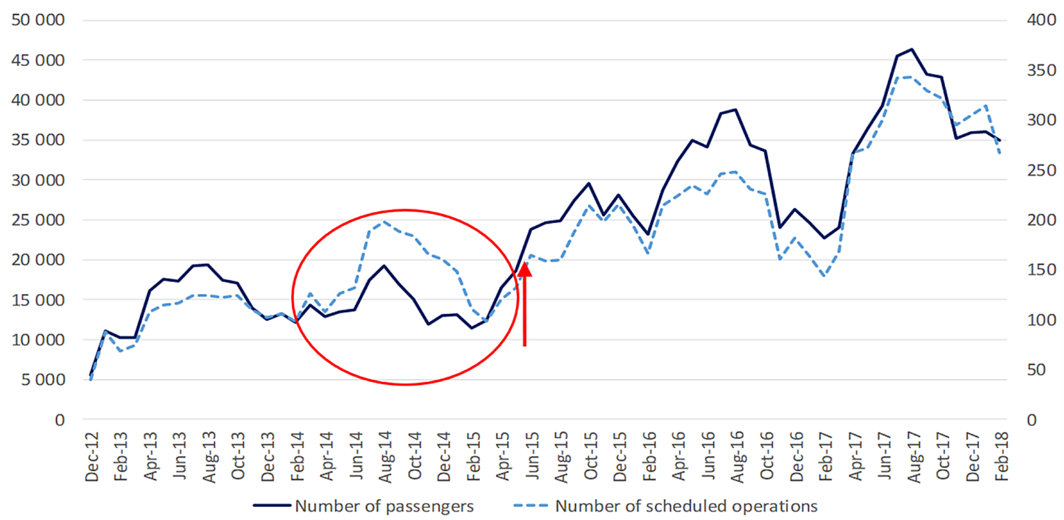

Figure 5. The period of the maladjustment of the time series course representing the number of air operations to the time series of the number of passengers served was highlighted. The arrow on the graph indicates the turning point of the trend determined with the use of the Chow test

H_0 is the number of passengers served by the Lublin Airport is a linear function with respect to the time expressed by the formula $y(t) = 487.38 \cdot t + 8785$, ($t \in [1; 66]$; (Figure 7).

In the presented article, the parameter t is a discrete feature, but more broadly it can be of continuous nature, hence, without limiting the generality of the considerations, the designations were assumed as for ranges and not for finite sets. As the previously observed breakdown should be (Figures 1–5) taken into account, an alternative hypothesis is made, which is a function of the variable t_0:

$H_1(t_0)$ is month, t_0 is the turning point month, which brings higher dynamics of the number of passengers served.

As for June 2015 ($t_0 = 31$; Fig. 6) F the Chow test statistics exceed the critical value, two time periods are distinguished [2012.12; 2015.05] and [2015.06; 2018.05]. They correspond to the phases of stability and dynamization of the number of passengers served (Figure 7). It means that the significance of the segment model (Figures 6 and 7) with the turning point at the turn of May and June 2015 with two linear components found with the Chow test:

$y[2012.12;2015.05](t) = 70{,}059 \cdot t + 14032$ (for the month number (t ϵ [1; 30])), and

$y[2015.06;2018.05](t) = 437.92 \cdot (t - 30) + 25192$ (for the month number (t ϵ [31; 66]),

describes the existence of a clear beneficial dynamic turn in the management process of the linear trend for a time series describing the number of passengers served at the Lublin Airport in the period of 2012.12–2018.05.

Attention should also be drawn to the high value of statistics F for November 2013 $t_0 = 12$; Figure 6). This date can be considered as the end of the initial, natural growth for the Lublin Airport, which translates into its crisis situation from the beginning of 2014 (Figures 1–5, 9). The first reaction of an analyst who sees a breakdown in the chart of a company's operations may be the supposition that the difficulties arose from the outflow of external financing of the entity (by municipal or provincial authorities). Therefore, this situation should be studied in more detail.

For this purpose, it is also possible to use a time series model with the trend in the form of a 12-month variable average or the above one obtained as a result of the Chow test and with an additive component of 12-month periodic fluctuations. Then, indicating the waves of increases and decreases among the 12-month periodic fluctuations in the number of passengers served, the analysis of the time series can be supplemented with the analysis of Elliot waves, thus creating a proprietary combination of these two different theories. It should be noted that the spring period of 2014 brought an increase in the number of operations (Figure 5) justified by "entry" into the beginning of the Elliot wave (Figure 8). However, during the entire 2014, the increase in the number

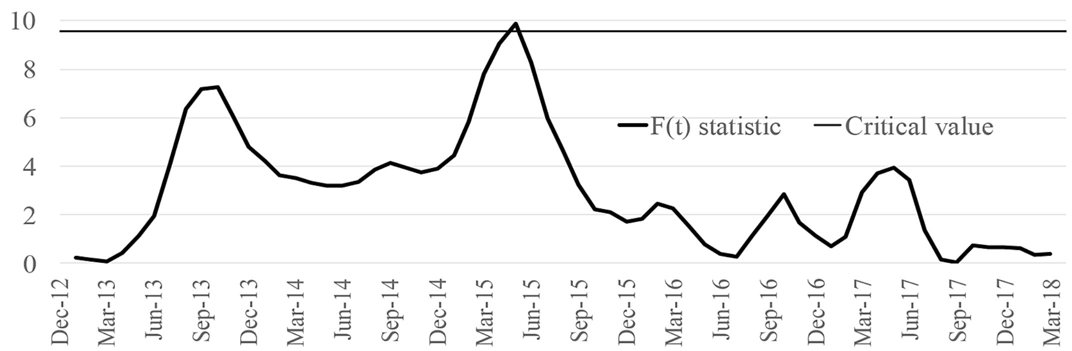

Figure 6. The values of the Chow test statistics $F(t)$ for the distribution of the number of passengers served. $F(t_0) = 9.89$ (for $t_0 = 31$; May/June 2015) is a value exceeding critical value 9.552 for the significant level $\alpha = 0.05$

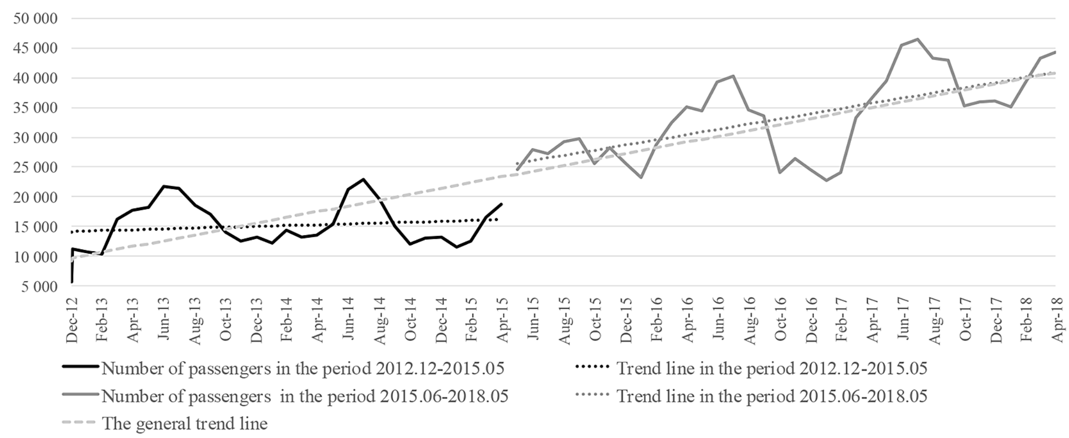

Figure 7. Graph of the number of passengers handled divided (by the Chow test) into two parts along with the trend lines for both parts and the general trend line

of operations is not accompanied by an increase in the number of passengers served (the highlighted area in Figure 5), which translates into a further reduced average passenger load factor (Figure 9). However, the increase in the number of operations is accompanied (at least to a certain point) by an increase in the number of ports connected to the Lublin Airport (Figures 1–2). Since the number of connections from the Lublin Airport grew, it should be acknowledged that the financing of the Lublin Airport was not affected. However, from just data analysis one can surmise a way of managing this complex network. On the basis of the research, it can be seen that two types of activities aimed at:

- goal (1) attracting future passengers,
- goal (2) attracting airlines with new routes.

Previously divided sensibly, were suddenly shifted disproportionately to goal 2), and the effect of increasing the number of passengers served (goal 1) was to be achieved as the expected inherent effect of the increased number of airports connected with LublinAP (goal 2). This, however, failed. This in turn indicates that such a shift of actions was an erroneous decision of the management, and the crisis situation did not result from the alleged changes in the external financing.

In addition, it is believed that also the time series expressing the total number of flight operations consist of Elliott waves, expressing an additive seasonality component measured every 12 months with the first rising wave starting in February (Figure 8).

In this work, it is pointed out that the rhythm of periodicity in the air traffic is systematically imparted by the Elliott waves. It should be noted here, that usually for stock charts, for which the Elliot waves theory was created, it is not easy to trace and describe these waves [64, 73]. A considerable problem is posed by the numerous alternatives that arise in the marking of the wave systems, as well as the fact that markets move perfectly wave only in a small percentage of time. The technique of finding Elliot waves proposed in this work with the use of statistical tools describing the seasonality element of time series can be a new way of detecting wave systems in the data superficially (Figure 2 and 5) not fitting this theory, e.g. in the longer term (here 66 months). It seems that the next analytical step would be to supplement the trend and the seasonality expressed by the Elliot waves, also with long-term cyclical fluctuations, which would allow for full forecasting of the observed phenomenon. However, this requires long-term observation of the process dynamics.

Ongoing control of the airport's business policy

Since it is not always possible to overlap 2 diagrams as in Figure 5 to indicate a problematic period, the use of unit or medium-term control cards as in Figure 9, is thus recommended, where apart from the mean, two (or three) standard deviations of the observed phenomenon are marked.

On the average monthly control card, i.e. one in Figure 9, being the result of the statistical process control [61–63], from July 2013 to November 2014, one can notice an almost monotonous decline in the passenger load of one statistical flight operation in the scheduled traffic at the Lublin Airport. This decrease resulted in egress beyond the area of acceptable passenger fluctuations from May 2014 to February 2015. Even a short period of the airport operation allowed the

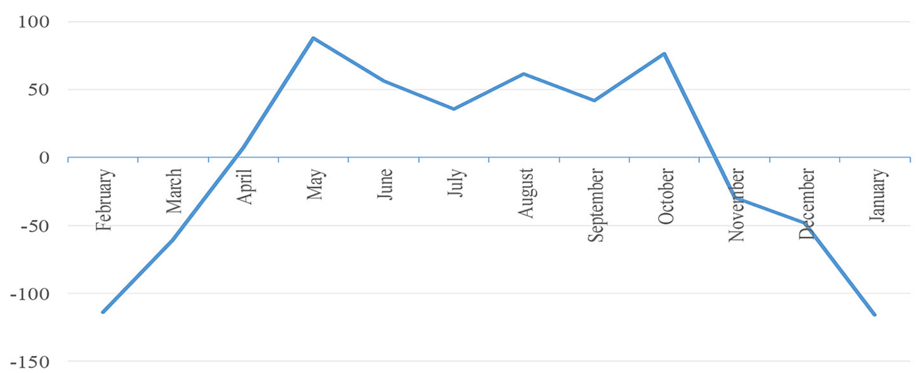

Figure 8. The additive seasonality component as a component of the time series of the total number of operations at the Lublin Airport in 2012–2018 expresses Elliott waves with three rising waves

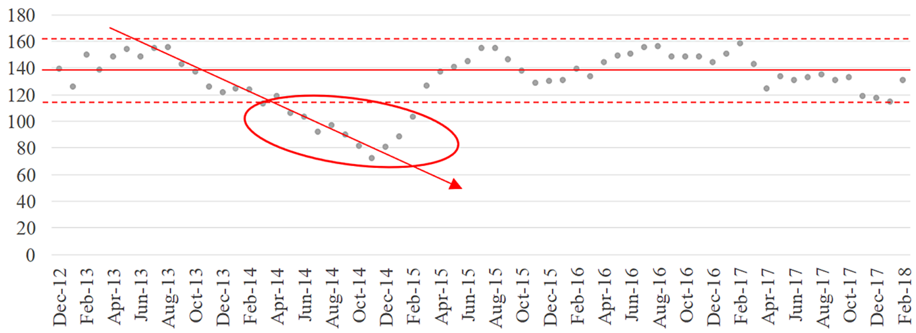

Figure 9. Monthly control card of the passenger load of one flight operation in the scheduled traffic at the Lublin Airport during the period December 2012 – February 2018 indicates a downward trend and a problematic period

managers to see the dangers resulting from the current policy of the airport after just a year of its operation, based on, for example, medium-term control cards.

Selection of a long-term business model for airports

In Figure 5 it is noted that in the period up to May 2015, the number of passengers served monthly at The Lublin Airport fluctuated in a stable range from 10 thousand to 23 thousand. After this period the linear growth dynamics of the number of a passengers is observed. In this case, the time series for the complex network in Figure 5 indicates the dependency between the date (i.e. an independent variable expressed on the interval scale) and the number of passengers served at the Lublin Airport (i.e. the dependent variable expressed in the highest row of scale, i.e. on the absolute scale). Due to the ordering of measurement scales resulting from allowed operations on variables from a lower scale to a higher order scale, the allowed direction of their transformation is opposite to this ordering, i.e. it is permissible to transition from a higher order scale to a lower order scale. Therefore, this dependent variable also has the properties of the quotient scale as well as both interval and log-interval scales [71]. On the other hand Luce in [43] noted that the only possible relationship between variables on interval scales can be in the form of a linear law, while the only possible relationship between an independent variable on the interval scale and a dependent variable on the log-interval scale can have the form of a law expressed by an exponential function. The latter relationship refers to the dynamization of the phenomena by orders of the magnitude, while linear laws describe monotonous changes. In Figure 5, it can be noticed that the deviation from the initially unknown and unidentified natural development rate of this airport each time necessitates the introduction of quick organisational adjustments.

Data from Figure 5 should be confronted here with the contrasting data in Figure 10 illustrating an unnatural and unsuccessful attempt, which was started in 1999 by the Irish low-cost airline Ryanair, to exponentially boost the number of passengers served at the German regional Frankfurt-Hahn Airport actually located about 125 kilometres west of Frankfurt am Main. The attempt, hailed as an enormous success, in fact brought a small initial short-term profit of EUR 0.4 million only in 2006 with a huge 3.5 million passenger traffic. It means that the traffic volume was up to 7 times the level of normal profitability. It also means that at that time only a minute profit of EUR 0.11/PAX was achieved, and subsequently after 2007 a systematic drop in passenger traffic was noted. Despite co-financing and subsequent takeover by regional self-governments, the financial problems of the operator of this German airport have been systematically and constantly escalated, exceeding the limits of ordinary bankruptcy [74–76]. It should be noted that the steady linear increase of the process accompanying the development of the complex network (Figure 5) allows one to discern the natural parameters of this phenomenon easily and appropriately adjust and optimise the necessary parameters of other side factors. On the other hand, the exponential development of the complex network (Figure 10) has parameters which are difficult to be accurately estimated and is usually subject to sub-optimisation. Even a small estimation error leads to significant differences in the sub-optimised forecast

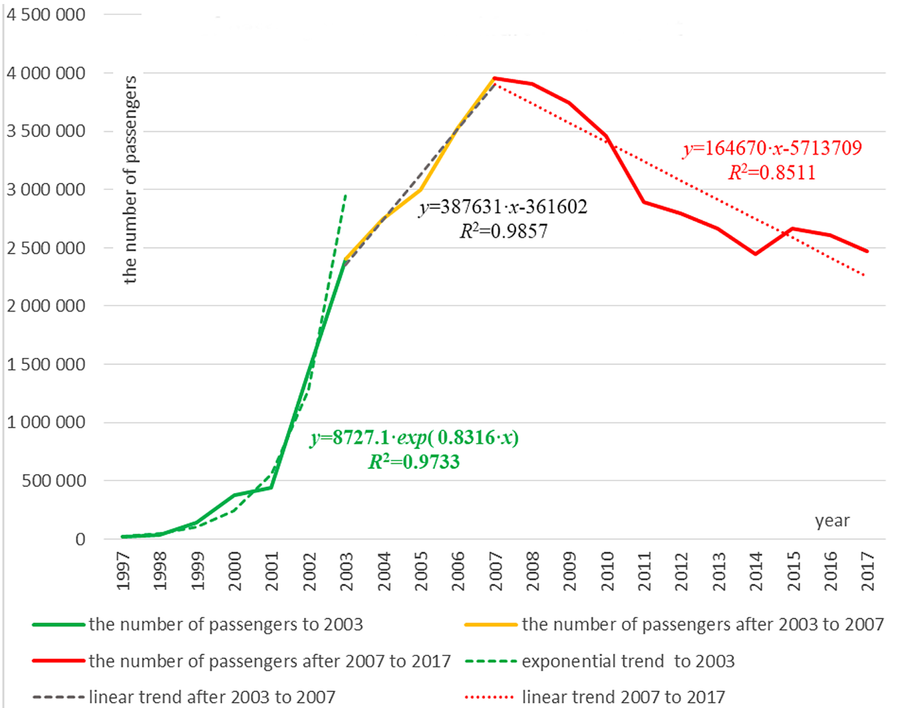

Figure 10. An unsuccessful attempt at exponential dynamization of the number of passengers at the Frankfurt-Hahn Airport in 1999 against the background of the actual number of passengers during the period of 1997–2017. The spontaneous two-step linear correction of this dynamics is observable. (It was assumed that x = year - 1996)

from the actual realisation. In addition, it is difficult to expect that simultaneous accurate and exponential intensification of many surrounding demographic processes and appropriate modification of the critical infrastructure for the development of the airport would be easy to obtain. With the progress of globalization and the development of complex distribution networks, the issue of transportation networks is becoming more and more important in the area of operations research [77]. Whereas encountering barriers in this area is quite common and stipulates adjustment. Hence, in this respect the authors recommend the use of managerial moderation according to Solomon's maxims: "Wealth gained hastily will dwindle, but whoever gathers little by little will increase it." otherwise "Whoever wishes to enrich oneself quickly, shall not escape punishment".

CONCLUSIONS

1. The observation of the complex network of the transportation system from the beginning of its existence allows us to notice that its development is governed by natural laws captured by the scheme of variant functions. The functioning of these laws can also be observed by developing a case study of regional airports in Central Europe.
2. Deviation from the natural course of processes (governed by the aforementioned natural laws) in a complex network occur in two cases:
   a) in an unstable manner as a result of external human interference (March/April 2014 and May/June 2015),
   b) in a permanent manner as a result of change in the actual operating conditions of the system.
3. A complex network demonstrates self-regulatory tendencies for external human interference (without changing the actual operation of the system). It is evident in the return to the initial increase after the annual stagnation for the Lublin Airport, drops to the natural level in 2007–2017 for the Frankfurt-Hahn Airport. Moreover, the greater the attempt to regulate natural processes without changing the actual functioning conditions of the complex network, the stronger is its reaction.
4. The natural linear development of the aforementioned aviation processes along with the commercialisation of regional airports and the condition of profitability seem to be the main factors of the stable growth of complex transport networks.

5. It is noted in the work that the seasonality expressing the repetitive dynamics of a complex network so far typically described in statistics with the use of the time series methodology can be captured in more detail in the Elliot wave terminology.
6. With the use of the Chow test, November 2013 is indicated as the moment revealing inappropriate organisation of the airport operation, i.e. the breakdown of the complex network organisation system. In historical data, even before the crisis itself at the beginning of 2014, it becomes visible when the first upward Elliot wave for the number of operations is not accompanied by an increase in the number of passengers served. Whereas the return to typical growth in the following year (May/June 2015) is the effect of self-regulation of this complex network.
7. The analysis of time series combined with the Elliot wave analysis allows us to determine unreasonable shifting of certain means, previously properly divided between various objectives of the airport, as the cause of the crisis for the Lublin Airport in 2014.
8. A distinctive growth parameter for the Lublin Airport (average increase in the number of airports in the world connected with the Lublin Airport by 1 every 9 months) is observed allowing reference and forecasting of further development of this regional transport hub. Similar parameters should be sought for other complex networks including larger transport hubs.
9. Observation of linear parameters of the initial period of the natural development of the complex network allows for avoiding overregulation of the functioning of transportation systems in the future. This is the parameter that should be paid special attention to by planners and managers of newly opened air transport ports, especially those of a regional nature.
10. In 2015 at the Lublin Airport a regional saturation of the market for civil aviation operations occurred in the General Aviation category at the level of 1750 operations a year, which is 5 flights per day with a total of 2.45 passengers on average. In 2016 the work on the construction of a cargo terminal was completed, whose launch allows the shipment of 1.2 thousand tonnes of goods per year although the potential of the entire region is estimated at even 3.5 thousand tonnes.

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