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SMART SUSTAINABLE CITIES: THE CONCEPT AND APPROACHES TO MEASUREMENT

Abstract
This article considers ICTs and the related Smart Sustainable city concept as tools to overcome urban challenges of the 21st century. The aim is to investigate different approaches applied to measuring "Smartness" and "Sustainability" of cities. Using our selection model, we identified 5 specific indexes for detailed comparison along with their results, namely which cities are the smartest and the most sustainable worldwide. We have also outlined the major concerns and limitations that exist in the indexes we covered in our research. This article is the first step on the way to developing a Smart Sustainable city index for Ukrainian cities.

Key words
Smart city, ICTs, informatization, sustainability, well-being, quality of life.

Introduction

Cities are sophisticated space-oriented formations that include a limited area, an urban environment (a complex of factors that impact objects and subjects presented within the area) and citizens. They quickly develop within time and space. The modern city can be compared with a lab, where the individual simultaneously creates and is a product of the surrounding environment [1].

Historically, cities were never considered as "places for developing human potential and talents". Ancient cities were created to protect citizens from foreign enemies. During the pre-industrial era, cities were centers of trade and crafts, and were later shaped as centers of industrialization. And only in the post-industrial era has the city become a center of intellectual development and innovations in all segments of the urban environment, marking a transitional stage for the establishment of a smart society [1].

Fast development of ICTs (Information and Communication Technologies), along with the cost reduction of mobile applications, free social media, cloud technologies and developments in the field of storage, processing and analysis of data have led to the emergence of new tools for understanding, communicating and forecasting urban functions [2].

Recently, the world has started to consider ICTs as tools of the 21st century that can help overcome the challenges posed by urbanization. Particularly, high levels of pollution, congestion, increasing demand for scarce resources, demographic changes, the ageing of population and related necessity of smart health solutions, and migration.

Related work

The topic has been actively studied and developed by many prominent academics, including Cohen [3], Giffinger [4], Lombardi [5], Schaffers [6], and Murray et al. [7]. Many famous institutions have taken part in the establishment of different indexes that measure sustainability and smartness, such as IESE [8], European Commission [9], ITU [10], OECD [11], and UN-Habitat [12], along with private institutions like Arcadis [13], Ericsson [14], and Huawei [15].

United Nations Habitat started a World Urban Campaign, including the "100 cities initiative," which is a forum for the best stories of changes in cities that aim for a smarter urban future [12]. The Smart Cities Challenge program was launched in 2010 by IBM with the idea of delegating experts to 100 cities around the world to help them deal with urbanization challenges [16].

Moreover, in the recently accepted 2030 Agenda for Sustainable development there is a specific goal (number 11) closely connected to the topic of our research, namely, “make cities and human settlements inclusive, safe, resilient and sustainable” [17].

Currently many cities are joining the "United for Smart Sustainable Cities" (U4SSC) initiative that encourages the use of ICTs to reach the goal of becoming smart and sustainable.

Objective and method

Different cities around the globe would like to join the concept of smart sustainable development to claim that they were able to implement “smart solutions” and prepare infrastructure for them so that they can be considered smart and sustainable.

But it is extremely difficult to confirm and validate such claims since there is not one generally accepted definition of “Smart Sustainable city” (SSC), and no common concept for comparing cities and their accomplishments.

Taking this into account, the aim of this article is to investigate different approaches applied to measuring smartness and sustainability of cities. The study compares the different methodologies and shortcomings to compose a Smart Sustainable city index for Ukrainian cities. The index will then serve as a tool to measure the progress of the concept’s implementation and will be comparable within the international agenda.

A method of theoretical, logical and systematic analysis of the literature (scientific papers, policy documents and statistical sources) was used to study various concepts of the “Smart Sustainable city,” along with the different methods for measuring “smartness” and “sustainability”. Methods of comparative analysis to compare various indexes among cities, along with descriptive and correlation analysis, were used in the article to consider the links between ICTs and selected socio-economic indexes.

Approaches to identify SSC

The concept emerged in the late 90s, while today it is being studied by academics, the business sector and governments. Each of these domains reviews the concept in a different way, which builds a broader common picture. Different terms can be encountered throughout the literature - “Digital city”, “Knowledge city”, “Green city”, “Creative city” - but even though the concepts might differ they all try to connect ICTs with economic, political and socio-cultural changes. Each concept aims to create a modern city with properly functional information processes and mechanisms that encourage creativity and innovations along with smart and sustainable solutions [18].

No doubt that technological solutions are the core component of the smart city concept. However, the definition of “smartness” cannot be limited only by the usage of ICTs. For example, Nam and Pardo in their work state that ICTs are only a tool for reaching the goal, not the goal itself [19].

Some authors add to the concept the word “sustainable” to the smart city concept, thus bringing the dialogue to a new level. We think it is important to investigate this question in more detail.

We find a definition of sustainable development in Brundtland Commission's report. It is stated that sustainable development is a "development which meets the needs of current generations without compromising the ability of future generations to meet their own needs" [20].

The International Telecommunication Union (ITU) outlines four main aspects on which the sustainability of a city is based:

- Economic: The ability to generate income and employment for the livelihood of the inhabitants;
- Social: The ability to ensure well-being (safety, health, education etc.) of the citizens can be equally delivered despite differences in class, race or gender;
- Environmental: The ability to protect future quality and reproducibility of natural resources;
- Governance: The ability to maintain social conditions of stability, democracy, participation, and justice [21].

As for the “smart” component in the concept, researchers distinguish two possible approaches [22]:
- Normative, which treats “smartness” as a desirable outcome and not as a tool;
- Instrumental, in which “smartness” is a tool to reach a set target, be it “sustainability” or something else.

In another work by Murray, Minevich, and Abdoullaev, three ways for cities to move to sustainability are described:
- Knowledge cities, which focus on lifelong learning and personal growth;
- Digital cities (cyber-cities), driven primarily by investments from large information and communications technology vendors aiming to connect everyone and everything by the means of high-speed networks, servers and data warehouses;
- Eco-cities, aiming for environmental sustainability using renewable resources [23].

But the authors stress that the ideal city requires the integration of all three approaches, which will lead to a new urban planning approach, namely, the smart city [23].

In 2014, ITU analyzed approximately 116 definitions of smart cities. They were obtained from a variety of sources including academic/research communities, government initiatives, international organizations, and corporate/company profiles. Six main factors for further analysis were chosen: smart living, smart people, smart environment and sustainability, smart governance, smart mobility and smart economy [10].

Based on the analysis, ITU suggested the following definition for a smart sustainable city: "A smart sustainable city is an innovative city that uses ICTs and other means to improve quality of life, efficiency of urban operation and services, and competitiveness, while ensuring that it meets the needs of present and future generations with respect to economic, social and environmental aspects" [10].

In sum, it is hard to provide one common definition for SSC because the concept possesses some qualities and characteristics to make life of a city’s inhabitants better. In general, the characteristics can be grouped within 4 dimensions: Smart People, Smart Economy, Smart Environment, representing so-called triple bottom line, and Smart Governance. To this we add an ICTs component as a helping tool (Fig 1.).

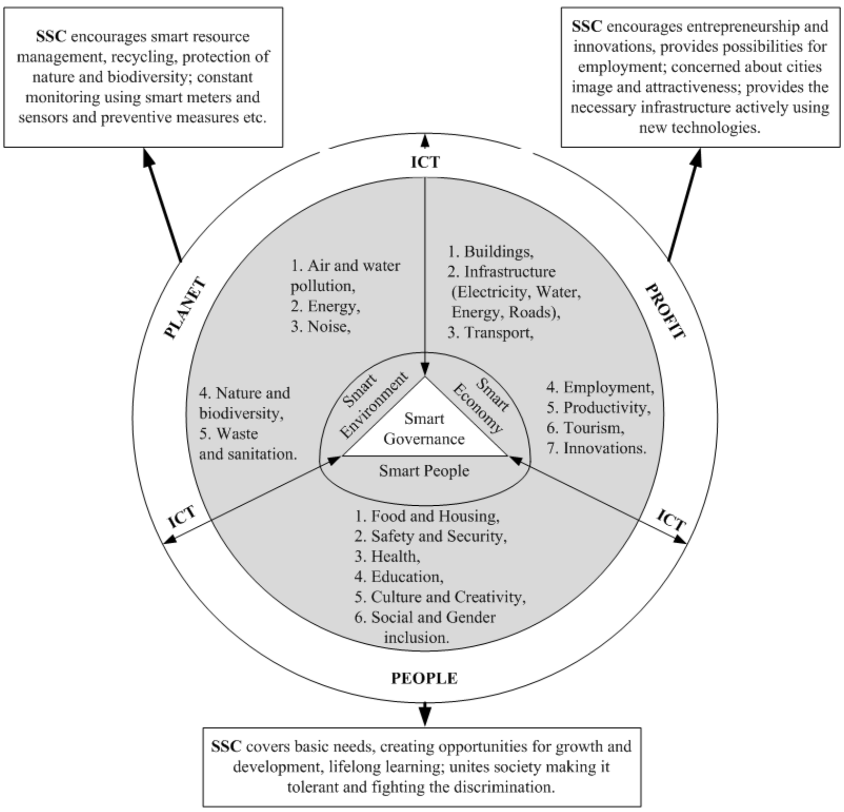

Fig.1. SSC components
Source: Author’s

A smart sustainable city:
- Meets the needs of its present generation;
- Provides equal opportunities for growth and development of each individual's potential;
- Does not compromise the ability of future generations to meet their needs;
- Does everything mentioned above in a smart way, using ICTs and other means.

*Smart way - the most optimal, safe way that does not break local and global environmental limitations.

We believe that "smart" answers the question "how?". "Sustainability," by contrast, answers the question, "What's the target?".

ICTs as a tool to improve quality of life
The spreading of ICTs (digitalization) is one of the most crucial stages in the process of preparing the foundations for the generation and usage of smart solutions. The next stage is informatization, which encourages communication and supports functionality. In the future, it allows taking into consideration social and environmental aspects, which is our final target.

Nowadays around 95% of the global population is covered by mobile-cellular networks, and around 40% of the world population is now estimated to be using the Internet. However, our world still faces digital gaps between developed and developing countries, as well as within some countries, based on gender and wealth [24].

In 2014, the adoption of The Connect 2020 Agenda was an important step. The Agenda specifies four main goals:
- Growth – enabling and fostering access to and increased use of ICTs.
- Inclusiveness – bridging the digital divide and providing broadband for all.
- Sustainability – managing challenges resulting from ICT development.
- Innovation and partnership – leading, improving and adapting to the changing technology environment [25].

Countries that adopted the Agenda committed themselves to the shared vision of "an information society, empowered by the interconnected world, where telecommunications/ICTs enable and accelerate social, economic and environmentally sustainable growth and development for everyone" [25].

Since 2009, ITU annually publishes reports that feature key ICT data and benchmarking tools to measure the information society, including the ICT Development Index (IDI).

IDI includes 3 sub-indexes:
1) ICT access (weight in index - 40%)
   - Fixed-telephone subscriptions per 100 inhabitants;
   - Mobile-cellular telephone subscriptions per 100 inhabitants;
   - International Internet bandwidth (bit/s) per Internet user;
   - Percentage of households with a computer;
   - Percentage of households with Internet access.
2) ICT use (weight in index - 40%)
   - Percentage of individuals using the Internet;
   - Fixed-broadband subscriptions per 100 inhabitants;
   - Active mobile-broadband subscriptions per 100 inhabitants.
3) ICT skills (weight in index - 20%)
   - Adult literacy rate 100;
   - Secondary gross enrolment ratio;
   - Tertiary gross enrolment ratio [24].

The diagram below (Fig.2.) shows the IDI distribution among countries. All countries roughly fall into three groups:

- Countries with low level of ICTs development (26%) - [1;3],
- Countries with average level of ICTs development (38%) - (3;6],
- Countries with high level of ICTs development (36%) - (6;10].

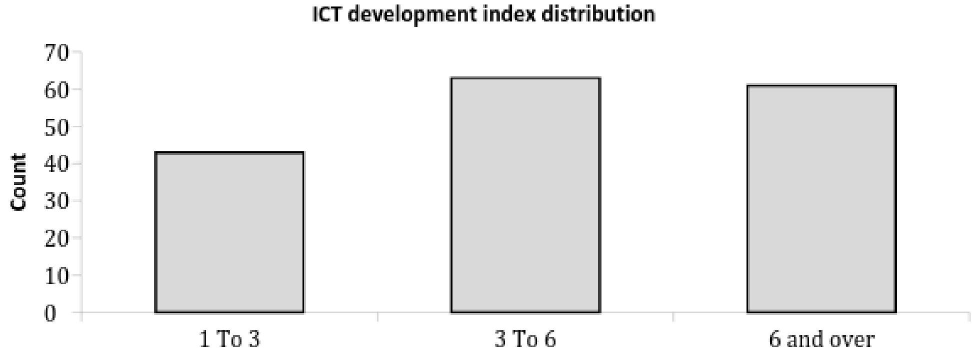

Fig.2. ICT development index distribution (2016)
Source: [24]

We have compared the level of IDI along with Human Development Index [26] and Corruption Perception Index [27] (see Fig.3. and Fig.4.), since these two indexes can be helpful in getting a general picture of the quality of life in different countries. Results show a positive correlation, indicating that there is a relationship. The correlation suggests that ICTs can be one of the tools for improving the wellbeing of people.

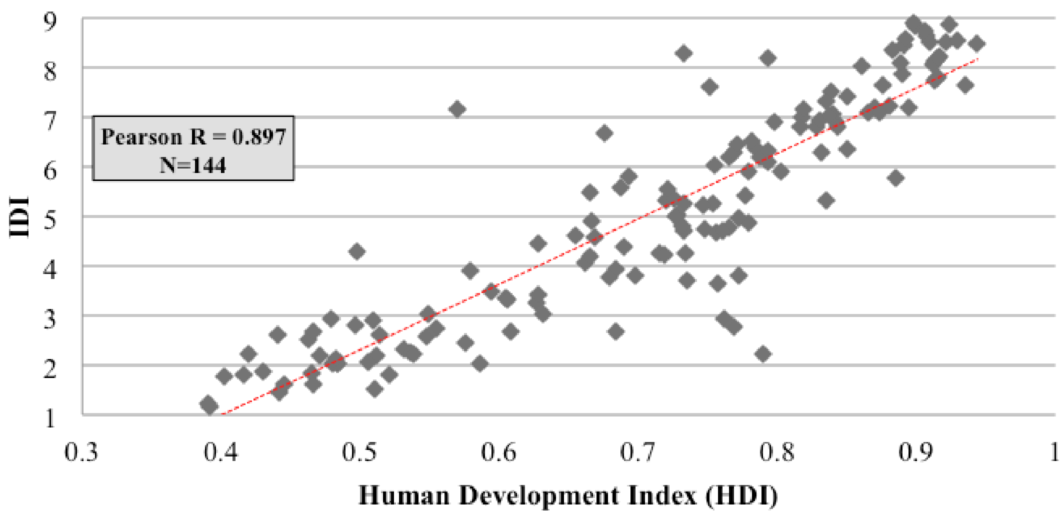

Fig.3. Correlation between IDI and HDI (2016)
Source: [24,26]

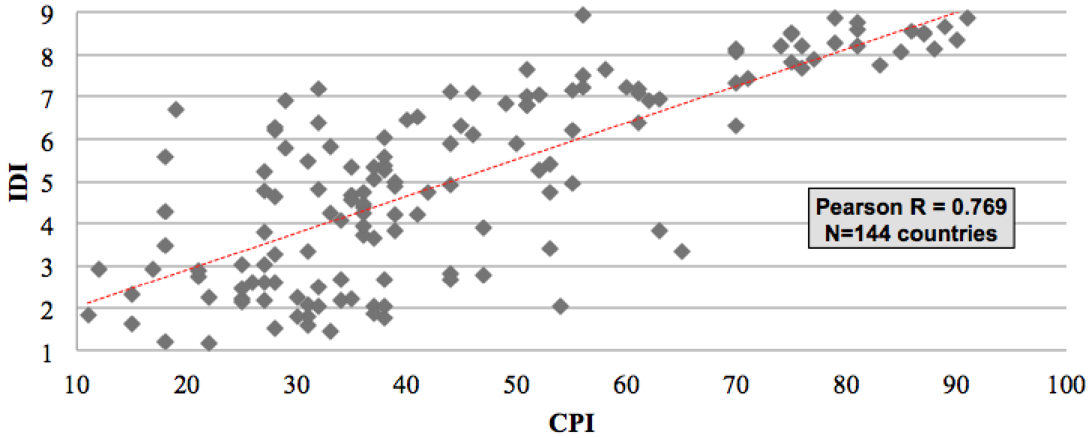

Fig.4. Correlation between IDI and CPI (2016)
Source: [24,27]

It is worth mentioning that dynamic ICTs development might also impose certain risks, particularly in the area of cybersecurity. The Global Cybersecurity Index (GCI) [28] measures the commitment of countries to cybersecurity. It is a composite indicator covering legal measures, technical measures, organizational measures, capacity building, and cooperation.

We have built a correlation chart between GCI and IDI. The results show that even countries with high level of ICTs development do not always have a good level of protection from cybercrimes (see Fig.5., Cluster 3). This question requires extra attention because any decision or tool should be not only effective but also safe.

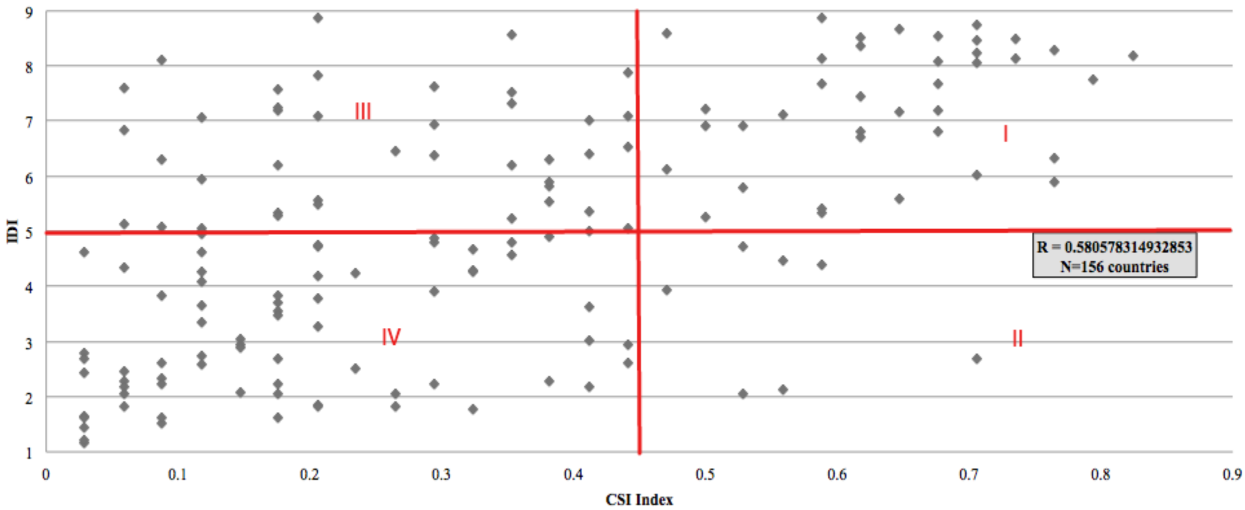

Fig.5. Correlation between IDI and CSI.
Source: [24,28]

Studies reveal that ICTs create new jobs on the market, save money thanks to moving off-line state services to online, encourage innovations in health and education, and incorporate smart systems in environmental protection and infrastructure, such as smart grids and intelligent traffic systems etc. [14].

Cooperation, digitalization, automatization, smartization, and the “Internet of things” are only several examples that ICTs bring to our society. Applied separately, however, none of these concepts guarantees improvements in sustainability or wellbeing. That is left to people and society, who must turn to wise governance to turn these concepts into the effective tools.

Measuring "Smart Sustainable cities"

Indexes allow analyzing trends and estimating the influence of political decisions that are taken to improve citizen wellbeing. They help identify the main areas that require more attention from managers and city leaders, as well as areas that are the most successful. Indexes serve as a tool to compare cities with each other on the initial stage of concept implementation and as a tool to measure the progress of a city within a defined time period. We outlined the ways in which indexes can be useful for different stakeholders (Fig.6.).

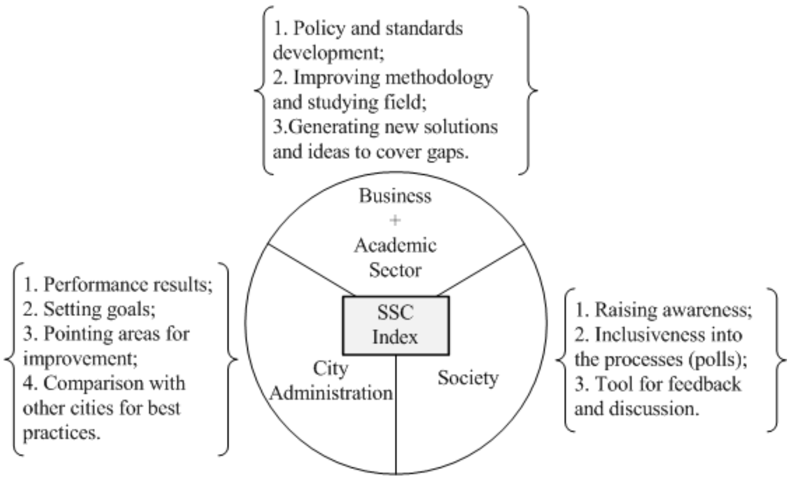

Fig.6. Index positioning in SSC concept for different stakeholders
Source: Author's

We can distinguish several types of indexes using different criteria. There are international indexes that cover cities from different countries worldwide, and national ones that rank cities within one country (e.g. Italy Smart system, and China smart system indexes). In terms of actors, we can outline indexes developed by the academic sector (e.g. Vienna University of Technology and IESE business school), by the private sector (e.g. Ericsson and Siemens) and government. Moreover, we can specify indexes that measure only one characteristic of smartness/sustainability or a complex of those.

In our current research, we decided to focus on international indexes that compare cities from different countries and estimate "smartness/sustainability" as a complex parameter. Below is the methodology of our selection process (Fig.7.).

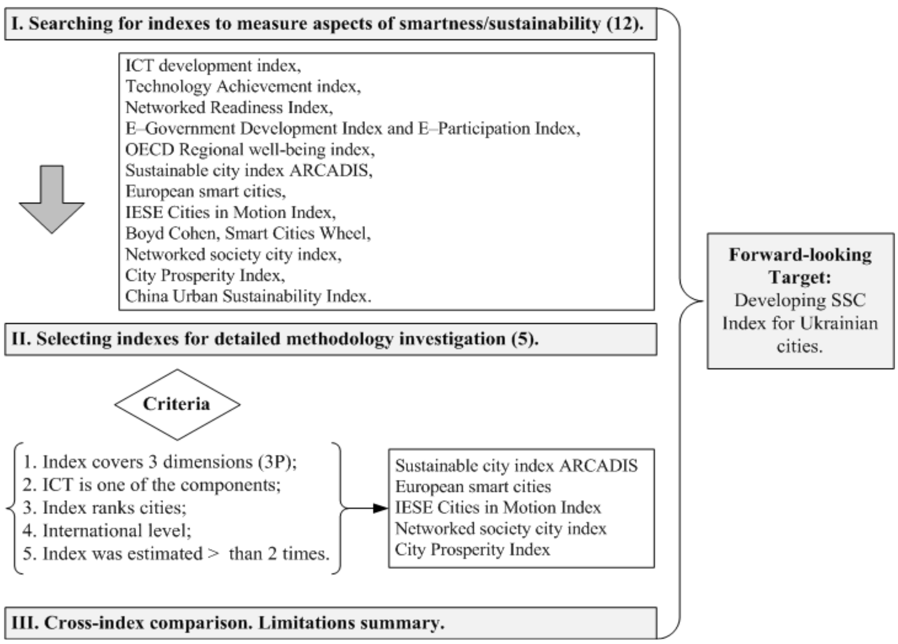

Fig.7. Selection methodology
Source: Author's

We provide more details for the selected indexes and summarize the information into the table in the following section.

ARCADIS sustainable cities index

The ranking is published by consultancy company Arcadis, starting from 2015 when the company selected 50 prominent cities worldwide. They were ranked as places to live according to their environmental footprint and financial stability, taken together. Due to the changes in the number of cities and parameters it is hard to compare the results dynamically. The rating is based on 3 components ("3P" concept): people, planet and profit. They cover social, economic and environmental aspects of development (see Fig.8.). In the 2016 report, 32 parameters were used to analyze 100 cities [13].

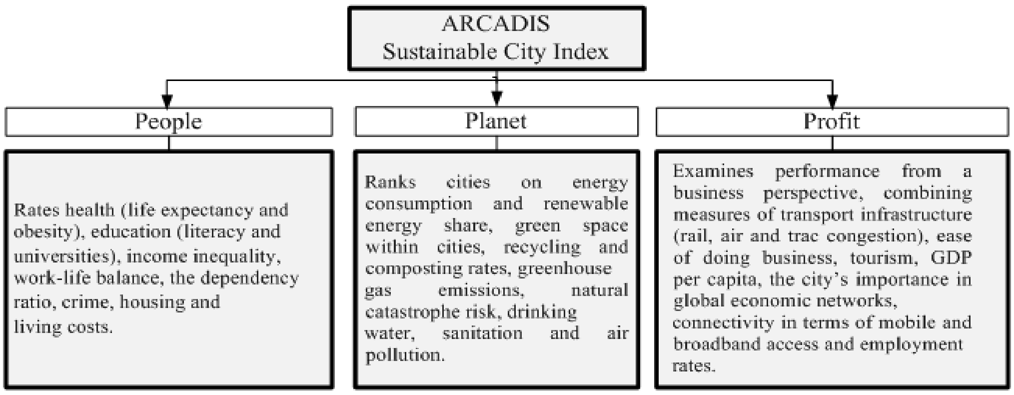

Fig.8. Arcadis sustainable city methodology
Source: [13]

Parameters within each category are averaged to calculate each component's score. Each city is then assigned a percentage score, which shows its place in relation to the others.

European cities dominate the general rankings, taking 16 out of 20 top positions, followed by prominent Asian cities like Singapore (2 place), Seoul (7th place), and Hong Kong (16th place).

The results show that most cities are unable to successfully balance between the three categories of "people", "planet" and "profit". Being a leader in one of these areas does not automatically guarantee leadership in others [13].

Table 1. Leaders in Acradis sustainable city index

General Index	People	Profit	Planet
Zurich	Seoul	Singapore	Zurich
Singapore	Rotterdam	Hong Kong	Stockholm
Stockholm	Hamburg	London	Geneva
Vienna	Vienna	Dubai	Vienna
London	Berlin	Zurich	Frankfurt
Frankfurt	Prague	Edinburgh	Wellington
Seoul	Amsterdam	Prague	Rome
Hamburg	Munich	New York	Sydney
Prague	Muscat	Paris	London
Munich	Montreal	Stockholm	Hamburg

Source: [13]

The researchers recommend that cities pay more attention to the "people" component since its development can help improve the other components.

Cities in Motion Index

This index was developed by the Spanish business school IESE in 2013. Its developers believe that civil society will be able to change cities from "smart" to "wise". The version of 2016 index covers 10 dimensions (77 components) and 181 cities [8]. The dimensions include:

1) Human capital. Human development is one of the priorities for every city. That's why smart management includes attraction and development of talents, improvement of the education system, and the encouragement of creativity and innovations.

2) Social cohesion. It measures the consensus that exists between different social groups and individuals. Within cities, examples may include consensus between people with different incomes, culture, age and profession.

3) Economy. Includes all the steps that are aimed to facilitate economic development of the area and, in perspective, lead to the increase in living standards.

4) Public management mainly deals with the effectiveness of city administration and includes tax policy, finance system, the international importance of a city, and opportunities for leaders to freely express their opinion in different sources (e.g. Twitter).

5) Governance, which typically shows the effectiveness of state intervention. But since in cities citizens are the focal point of all events, this dimension covers public participation and involvement of civil society, along with the business sector, as well as the implementation of e-governance.

6) The environment. This dimension covers measures that are necessary to fight pollution, such as support for green buildings, renewable energy projects, and the effective management of resources.

7) Mobility and transportation. Requires a balance between the needs of the citizens to reach a necessary point of destination and the resulting levels of pollution that are caused.

8) Urban planning. The main target of this dimension is the improvement of the living area, such as the establishment of compact, well connected cities with available public services.

9) International outreach. Covers the position of the city on an international arena, brand creation, and its acceptance and openness.

10) Technologies allow estimating ICTs availability and coverage, along with the quality of the provided web-services.

IESE analysts apply the DP2 technique for index estimation. Methodology is based on the difference between the actual value of the indicator and set targeted value. After this, cities get split into 4 categories: high performance (index>90), relatively high (between 60 and 90), average (between 45 and 60) and low (below 45).

The top ten cities include four European and four US cities, with New York taking the top place.

The following conclusions were drawn from the analysis:

1) It is impossible to build one model of success. Cities should begin from the vision of what exactly they would like to build and what should be improved.
2) It's not enough to be a leader in one of the directions, because this causes unbalanced development and does not lead to sustainability.
3) There are no ideal cities and changes happen very slowly.
4) Cities do not operate isolated, that's why city leaders should be able to estimate possible threats and opportunities within the national context [8].

Networked society index
In 2016, Ericsson and Sweco (leading consultancy in sustainable development) conducted a new research that covered 41 cities. The main target of this index is to measure the performance of cities from two perspectives: their ICT maturity and their sustainable urban development (the Triple Bottom Line) [14]. ICT maturity is measured based on infrastructure, affordability and usage, while the Triple Bottom Line covers 3 dimensions: social, economic and environmental (see Fig. 9).

This is a hierarchical index model, where sub-indexes possess different weights. The authors use geometrical aggregation and a “Min-Max” normalization model.

The aim of the study is to find how ICTs can help speed up the achievement of Sustainable Development Goals.

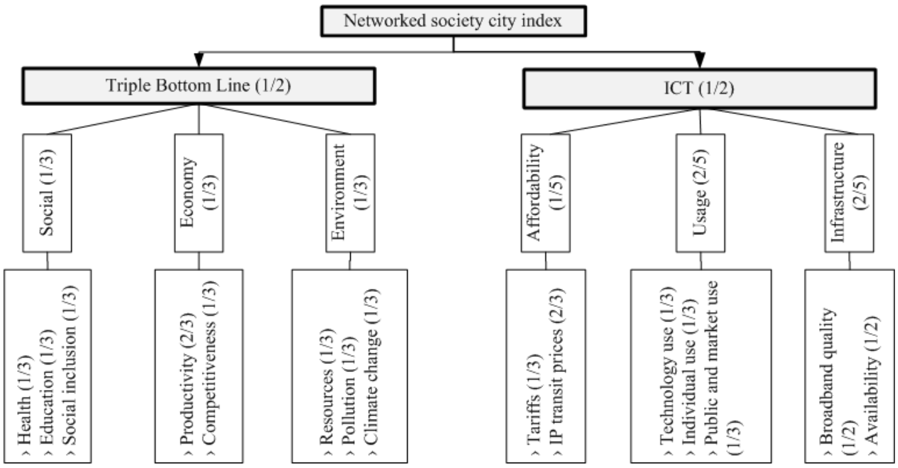

Fig.9. Index methodology
Source: [14]

It is worth mentioning that none of the cities in the ranking can be considered environmentally sustainable, even those taking the leading positions.

The study reveals that ICT maturity has higher correlation with socio-economic development than with environmental sustainability. Nonetheless, Ericsson states that ICTs have positive impact on the levels of CO2 emissions and may allow decreasing those by up to 15% by 2030 [14].

Among the top-10 there are six European cities, with Stockholm taking the top position, and three Asian cities.

City Prosperity Index
The index was founded by UN-Habitat in 2012 as a tool to measure the city’s sustainability [29]. In 2013, the organization received numerous requests from the cities worldwide to estimate their level of prosperity and this made initiative global. The tool is based on four scenarios:
- Global city ranking (local and global monitoring),
- Basic City Prosperity Index (initial analysis, results are internationally comparable),
- Extended City Prosperity Index (In-depth Diagnosis Comparable within country),
- Conceptual City Prosperity Index (Policy performance and urban monitoring tool).

The version of 2015 covers 60 cities worldwide. Dimensions used for the index are presented in the table below.

Table 2. Components of City Prosperity Index

Category	Sub-category	Indicator
Productivity (1/6)	Economic Strength	City Product per capita
	Employment	Unemployment Rate

Category	Sub-category	Indicator
Infrastructure (1/6)	Housing Infrastructure	- Improved Shelter - Access To Improved Water
	Social Infrastructure	Physicians Density
	ICT	Internet access
	Urban mobility	Traffic fatalities
Quality of life (1/6)	Health	- Life Expectancy at birth - Under-Five Mortality Rate
	Education	- Literacy Rate - Mean Years of Schooling
	Safety and security	Homicide Rate
Equity and Social Inclusion (1/6)	Economic equity	- Gini Coefficient - Poverty Rate
	Social inclusion	- Slum Households - Youth Unemployment
	Gender Inclusion	Equitable Secondary School Enrolment
Environmental Sustainability (1/6)	Air Quality	PM2.5 Concentration
	Waste management	Waste Water Treatment
	Energy	- Share of Renewable Energy - CO2 Emissions
Governance and Legislation (1/6)	Participation	Voter Turnout
	Institutional Capacity	Days to Start a Business

Source: [29]

Cities are classified using the scale 0 - 100, where levels between 80 and 100 mean very solid prosperity. Among the leaders six European cities, Oslo takes first place. We have created a common table for the indexes described above.

Table 3. Indexes measuring smartness/sustainability

Index	Created by	Year/frequency	N of cities	What's measuring
Arcadis Sustainable Cities Index	Arcadis and the Centre for Economic and Business Research	2015/annually	100	Urban sustainability that encompasses measures of the social, environmental and economic health of cities.
Cities in Motion Index	IESE Business School	2013/annually	181	Future sustainability of the world's main cities as well as the quality of life of their inhabitants.
Networked society city index	Ericsson	2011/annually	41	Describes the development status of cities worldwide in terms of their ICT maturity and triple bottom line effects derived from ICT.
City Prosperity Initiative (CPI)	UN-Habitat	2012, 2015	60	The way cities create and distribute socio-economic benefits or prosperity and the overall achievements of the city.
European Smart cities	Vienna University of Technology	2007, 2013/annually	90	City functioning in six characteristics (smart economy, smart mobility, smart environment, smart people, smart living, smart governance).

Source: Author's based on [8, 13, 14, 29]

We have built a table with the leading cities from different indexes to compare the results. By color we have selected cities that met at least three out of four indexes (see Table 4).

Table 4. Cross-index results comparison

Arcadis sustainable city index	Cities in motion index	Networked society index	City prosperity index
Zurich	New York	Stockholm	Oslo
Singapore	London	London	Copenhagen
Stockholm	**Paris**	Singapore	Stockholm
Vienna	San Francisco	Paris	Helsinki
London	Boston	Copenhagen	Paris
Frankfurt	Amsterdam	Helsinki	Vienna
Seoul	Chicago	New York	Melbourne
Hamburg	Seoul	Oslo	Montreal
Prague	Geneva	Tokyo	Toronto
Munich	Sydney	Seoul	Sydney
100	181	41	60
8 European cities	4 European cities	6 European cities	6 European cities

Source: Author's based on [3, 11, 15, 16]

In all indexes, European cities prevail in the leading top-10 list. Stockholm, London, Seoul and Paris are the cities that are met 3 out of 4 indexes.

There is also another index (European Smart cities by Vienna University of Technology), which does not fully qualify according to our methodology to be included into our study due to its geographic limitations (only European cities of medium size are included). But we still consider the index as worth mentioning in our work due to the detailed methodology it is based on.

Accordion to the concept, "A Smart City is a city well-performing in a forward-looking way in six characteristics (smart economy, smart mobility, smart environment, smart people, smart living, smart governance), built on the "smart" combination of endowments and activities of self-decisive, independent and aware citizens" [30].

The study includes 74 indicators that were combined in 31 factors to illustrate 6 criteria mentioned above. The study of 2015 included 90 medium-sized cities (300.000 – 1 mln) from 21 countries. The first study was conducted in 2007. In 2015, the top-10 list included three cities from Denmark, three cities from Finland, and two cities from Austria, along with Luxembourg and one city from Norway [30].

Limitations of indexes measuring smartness/sustainability

Having examined many indexes, we think it is important to describe the constraints that exist in such indicators since they should be taken into account when creating the index for Ukrainian cities.

1) From methodological point of view, a high correlation takes place between the components of the index. This should be taken into account when assigning weights to the components in the general index to avoid the double-counting issue. There is also lacking one common, clear, user-friendly, statistically significant procedure for aggregation and weighting of the different components. It is the subjective decision of the researcher [31];

2) From statistical point of view, it is often impossible to receive all the necessary data on the city level. Most data are available on the regional, district or national levels. Researchers must use average values, which can lead to distortions of the final result accuracy.

3) In terms of comparability, in most cases it is impossible to compare the results for different years, due to the changes in methodology and the number of cities that participate.

4) In terms of coverage, most studies focus on big prominent cities (typically capitals), avoiding medium and small-size cities [32].

Conclusions

Indexes are great and important tools for city leaders and managers to monitor weaknesses along with the impact particular steps might have on city positions, and for the business sector and academics to develop smart solutions for particularly problematic areas. They serve as indicators for society to raise awareness and engage people in the development and decision-making processes. They could be a starting point for the common dialogue to make our cities safer, more environmentally- and citizen-friendly, as well as a great tool to monitor progress.

The current article reviews the SSC concept and provides the authors' interpretation of the term and concept. Our main aim was to investigate different concepts and methodologies that allow measuring Smart Sustainable Cities and comparing them worldwide. We have conducted an initial index selection process, setting the criteria to find the indexes that suit our studying purposes the best. As a result, we have selected five indexes, analyzed them in more detail, and presented the summarized results into the table. We have also created a comparison table for the results that indicate common trends, even though different methodologies are applied.

In our opinion, all indexes have their own advantages and disadvantages. For example, in the Arcadis Sustainable Cities Index, Cities in Motion Index and City Prosperity Index, the "Technology" component is quite poorly presented and has low weight. The Networked Society Index and Arcadis Sustainable Cities Index lack a "Governance" component in their methodology. European Smart Cities Index is the only index that includes medium sized cities instead of just capitals, and also includes quite interesting components (open-mindedness, engagement in creativity industries etc.), but they are difficult to measure in cities beyond the European Union.

We would like to base our future index on the idea of multi-level analysis, varying from a simple comparison tool to a proper performance analysis tool (based on City Prosperity Index) and the model of Ericsson Networked Society Index (due to the high weight/importance of Technology component), but including a Governance component. It is desirable to take as a basis internationally approved methodology to ensure in the future that our cities are comparable within international frameworks. But our current goal is to create a tool to analyze the cities and set the standards for them within the national boundaries, which allows us to monitor progress.

We also believe that our first and foremost aim should be not for the Smart Sustainable cities themselves, but for the encouragement and development of intelligent behavior and smart citizens that will be able to implement and develop this concept in future.

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AQUACULTURE WASTE MANAGEMENT

Abstract

Fish and seafood production has grown steadily in the past five decades. Total world fisheries and aquaculture production reached 167.2 million tonnes in 2014 [1]. Intensive fish production triggers growth in the amount of waste processing, which has serious environmental impacts. Utilization and energy recovery from fish waste have become areas of interest for the global economy. Specialized methods and techniques have been developed to acquire biomethane, biodiesel and biofertilizer from fish biomass. Also, using physical, biochemical and thermochemical processes, relevant substances (such as fish protein hydrolysate, natural pigments, chitosan and collagen) can be obtained.

Key words

fish waste uses, fish waste management, biogas, collagen, chitosan

Introduction

One of the biggest global challenges humanity currently faces is global warming. According to the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) analysis, 15 of the 16 warmest years ever recorded occurred during the last 35 years [2]. Rising surface temperatures on the Earth are caused by the increased emission of greenhouse gases related to human activity. Waste generation and management have serious environmental impacts. Furthermore, the rising human population will produce an increasing amount of waste. Decaying organic waste generates large quantities of carbon dioxide and methane, which contribute to climate change. Industry waste obtained from the fishing sector could be used as a renewable resource.

Fish and seafood are major sources of food and nutrition and are part of a healthy, balanced diet. The fishing sector provides an income and livelihood for hundreds of millions of people around the world. A new record in world fish consumption of 20 kg per capita was reached in 2014 [1]. Unfortunately, the rapid increase in fish production is connected with farm-raised rather than wild-caught fish. The aquaculture waste generated is very heterogeneous in its properties and form, depending on the region and species. Many factors influence the quantity and quality of the waste, such as fish size, season, rearing techniques, husbandry, catching and manufacturing methods. More than 50% of the residuals from the total fish capture is unused as nourishment and involves near 32 million tonnes of waste [3].

The type of culture methods also plays a key role in defining fish waste and in choosing the most effective method to transform them into a usable product [4]. Intensive marine fish farming maximizes the number of fish in the smallest possible area. Big fish farms produce enormous amounts of particulate organic waste and soluble-inorganic excretory waste [5]. After processing or industry treatment, the remainder represents near 50% of the tonnage utilised to production. The disposal consists of fish offal such as heads, frames, tails, skin, lugs, bones, fins and viscera.

Fish industry waste is thought to be the main source of biofuel in near future. The growing production of waste and requirements to use renewable energy sources force governments to implement waste management programs. In addition, the waste management sector is obligated to reduce landfilling for residual disposal. Fish waste might be an important source of environmental contamination, provoking the need for specialized methods for transforming fish disposal into a usable product.

Fortunately, energy recovery from fish processing waste is gaining popularity. Many developed countries use anaerobic digestion as an approach for fish waste treatment. Decaying solid biomass generates a large amount of methane, which can be transformed into thermal and/or electrical energy. In addition to electricity or heat, there is a possibility to obtain selected substrates for the cosmetics, pharmaceutical and food industries from fish waste. The recovery of merchantable by-products from aquaculture wastes plays a key role in waste reduction strategies. In the current study, different fish waste management scenarios were described in the form of a mini-review. The main target of this review is to compare existing solutions for industrial implementation and choose the optimal treatment for fish waste.

Waste management

Fish Waste Management focuses on the generation, treatment, specification, controlling, prevention, handling, reuse and ultimate residual disposition of fish waste. Over the past 30, years many directives were initiated under the auspices of the European Union. These directives refer to the management of aquaculture waste and the environmental impacts of fishery brands [6]. The growing utilization of by-products requires the implementation of guidelines for fishery policies. However, an optimal waste management system depends on both the costs and predicted benefits.

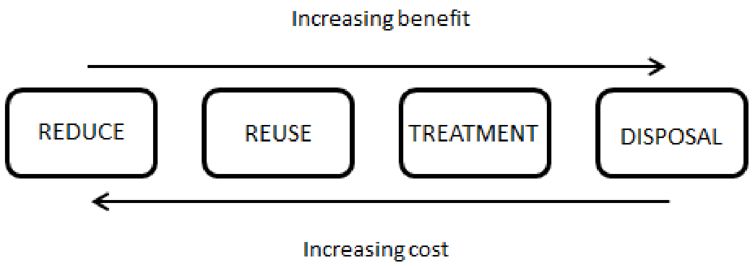

Fig. 1. The priories for fish waste management
Source: Author's

Aquaculture and related industries process waste, which is suspected to pose a significant risk to the ecosystem. To mitigate pollution, appropriate technologies should be used. The conversion of these wastes and the simultaneous recovery of significant materials before disposal become the main aim for fishery management [7].

Biogas

Biogas consists of different compounds, mostly methane CH_4, carbon dioxide CO_2, and a little hydrogen sulphide H_2S and hydrogen H_2, that are produced by the breakdown of using anaerobic digestion. Fish waste is potentially an appropriate source for methane production due to its high content of organic carbon. However, fishery biomass is high in ammonia nitrogen, which limits biogas production. There is a possibility to apply anaerobic treatment of fish disposal using co-digestion. The key issue for the co-digestion process is the proper composition of the co-substrate mixture. It is important to balance the main parameters such as the C:N ratio, macro- and micronutrients, pH, biodegradable organic matter, toxic compounds and dry matter [8].

A general scheme of biogas production is shown below (see Fig 2.) Biogas plants treat different types of biodegradable waste, including energy crops, animal manure, sewage sludge, organic residues and municipal solid waste. The co-substrate mixture requires processing such as chopping, liquefying, mixing and inoculation. Biogas technology involves a fermenter, temperature, hydraulic retention time, amount of substance and shut off from light and air. The quality of biogas is determined by the percentage composition of CH_4, CO_2, NH_3 and H_2S.

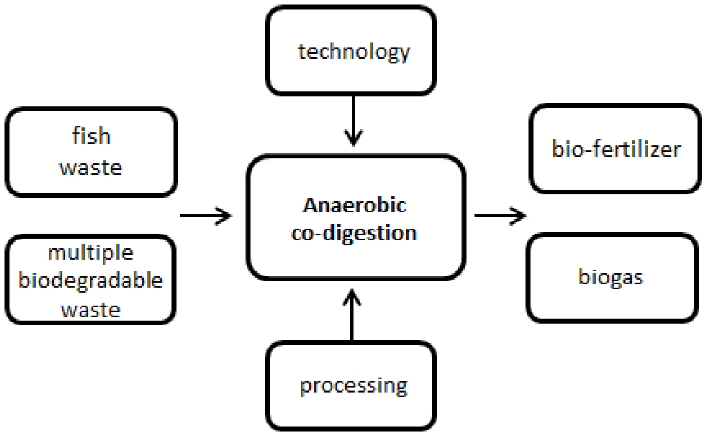

Fig. 2 Anaerobic co-digestion of fish waste
Source: Author's

The most commonly used tool to measure the anaerobic degradability of a feedstock is the Biochemical Methane Potential (BMP) test. The BMP creates batch digestion, in which substrates are incubated with anaerobic microorganisms. An indication of the rate of feedstock digestion is the precisely measured volume of biogas generated [9]. The main advantages of this method are simplicity, cost, repeatability and the short period of time to determine the appropriateness of a substrate for anaerobic digestion. The methane potential is showed in terms of standard temperature and pressure (STP) ml CH_4 per 1 g of VS added (mL CH_4 / g VS) [10].

Recently, many lab scale evaluations of BMP of fish waste were published. Most of theme relate to co-digestion of fish offal with animal manures, sewage sludge, organic residues and different food industry wastes. The aim of those works was to select optimal co-digestion substrates to improve biogas production from aquaculture waste. The research results demonstrate the optimal ratios of various co-substrates for the enhancement of methane potential [11]. The biochemical methane potential of various solid fish waste was also studied. Feedstock with 1% of total solids (TS) of waste had the highest methane production. It was very similar for sardine, tuna, and needle fish waste, likely due to higher fat content [12].

Despite the fact that research on using fish waste as a source of biogas production has promising results, there are limited industrial applications. High investments costs involved in building biogas plants and the limitation of biogas production due to high concentration of ammonia nitrogen in fish waste are likely factors.

Biofertiliser

As biogas plants grow more popular, the residues after anaerobic digestion are also reused as an essential source of a nutrient-rich substance. After a few unit operations, digestate could be applied as a biofertiliser. The properties of digestate depend on the nature and composition of the digested substrates [13]. Digestate consists of structural plant matter, process intermediaries, dead microorganisms and indigestible material. The total volume consists of more than 90% of the feedstock. Elements such as nitrogen, phosphorous and potassium remain in the digestate. Fish nutrient-rich waste has high-quality digestate, which could be transform into commercial fertiliser. The first step in the transformation is mixing the end-product of digestion together with organic waste using the same minerals to obtain the appropriate level of NPK (Nitrogen, Phosphorous and Potassium). The composition of digestate depends on the source materials and the digestion process, but the average values for nutrients are in a similar level [14]:

- Nitrogen: 2.3 - 4.2 kg/tonne
- Phosphorous: 0.2 - 1.5 kg/tonne
- Potassium: 1.3 - 5.2 kg/tonne

A mixture of thick liquid consistency is then dried using energy from the biogas plant. The last step of the process is to achieve small granulation of biofertiliser, which is important for practical use and for transportation and storage. Even though nutrients are more available for plants from raw slurry, biofertliser releases nutrients slowly and reduces their impact on the environment.

While post-digestion matter is rich in both organic matter and macro- and micronutrients, it can also contain heavy metals. The problem arises from anthropogenic sources as a part of the feedstock. The main origins of the heavy metals are fish farm waste, fat residues, domestic sewage, food industry, animal feed additives and flotation sludge. Research conducted in Europe shows that with respect to heavy metal toxicity, digestate seems to be a good candidate for a fertiliser. Although the total concentration of cooper, zinc and cadmium were at the limit set by European regulation, these elements after digestion were mostly unavailable for direct absorption by plants [15].

Sustainable agriculture is obligated to provide healthy and safe food using post-digestion matter instead of synthetic fertilisers. Residues from biogas plants save energy, reduce our carbon footprint and cut consumption of fossil fuels. Consequently, the quality of biofertiliser is related to co-digested waste. The only condition in using biofertiliser is the rational utilization of such residues [16].

Bio-oil/biodiesel

The fish processing industry generates large quantities of fish oil. This by-product could be used as a renewable energy source. Many studies have been carried out on the properties of fish oil as a fuel because of its high hydrogen and low carbon content. It has much lower kinematic viscosity and a higher flash point [17]. Bio-oil has appropriate properties as a fuel for diesel engines. Compared to traditional diesel fuel, it has a higher heating value and is higher quality than methyl esterificated vegetable oil waste. Biodiesel from fish waste could be used in diesel engines, mainly at low temperatures. The potential for biofuel from fish waste is a function of the location and size of the processing plant, type of fuel requirements, and characteristics of the fish waste. Biofuel is derived from biomass using many different chemical, biochemical, thermochemical, and physical processes [18].

The first process is pyrolysis of biomass. The thermal breakdown takes place at high temperatures (350–700 °C) in anaerobic conditions. Products of pyrolysis consist of biogas (CO, CO_2 and CH_4), biochar (carbon and hydrogen), and bio-oil (organic acids, alcohols, esters, alkenes, ketones, aldehydes, phenols, nitrogen compounds) Nowadays, fast pyrolysis is the most promising thermal conversion technology for biomass.
Fast pyrolysis lasts a few seconds, so heat and mass transfer parameters play key roles in the process. The selection of the apparatus is also important. The process, necessary preparation steps and types of products obtained are shown in the simplified scheme below (see Fig. 3.).

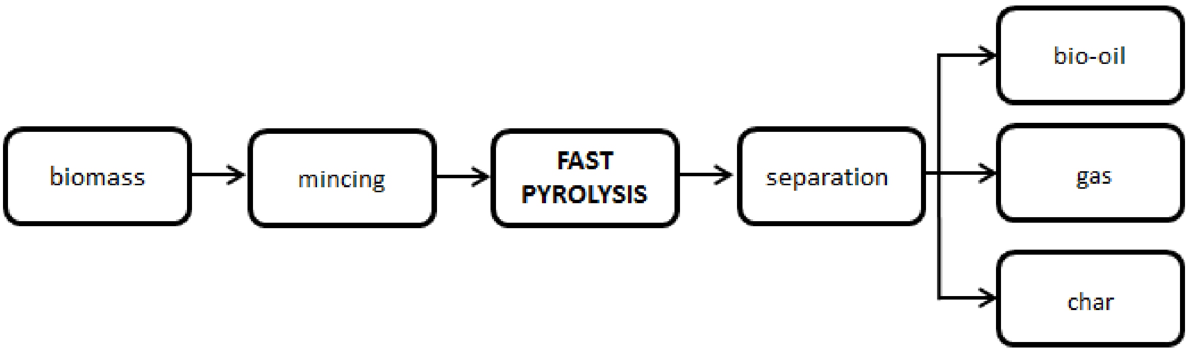

Fig 3. Fast pyrolysis process
Source: Adapted from IEA [19]

Afterward, the recovery of oil from waste biomass can be used in the fermentation and hydrolysis processes. Bacteria generate silage during the utilization of sugars or organic acids, where oil could be recovered as a by-product. Different steps are involved in oil extraction and oil refining to obtain purified bio-oil. They consist of various operation units as pressing, filtering, degumming, neutralizing, bleaching, hydrogenation and deodorizing [19].

The interest in processing of biomass for biofuel is steadily growing. Fish processing oil is predicted to be an alternative source for biodiesel. Despite the great potential of biofuels, there are technical and economic challenges. The specialized methods and very specific parameters of every unit process make the production problematic and relatively expensive.

Protein hydrolysate

Protein hydrolysis means breaking protein into peptides and free amino acids. Protein recovery became one of the main target for enzyme technologies due to the growing production and wide use of protein ingredients in the food industry. The main purpose of producing protein hydrolysates is to improve nutritional and biological value and to produce added value merchandise because of a wide variety of applications such as milk replacers, stabilizers in beverages, protein supplements and flavour enhancers [20]. The key process is to form specific size peptides, either by enzymatic or chemical methods [21]. Biological methods using enzymes are prevalent, and products of enzymatic hydrolysis have higher nutritive value and functionality.

To obtain hydrolysates from aquaculture industrial waste, the process is as follows: isolation or pre-treatments, hydrolysis, protein recovery (see Fig 4.). In each process, specific parameters should be fulfilled.

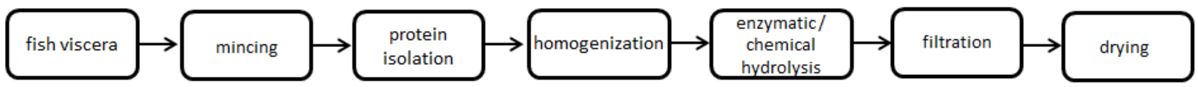

Fig. 4 Fish protein hydrolysate production
Source: Based on [22]

Proteins from animal sources are more nutritious than from plants due to the better balance of the dietary essential amino acids. A continuous development in protein hydrolysis resulted in obtaining the desired products for various applications. Many studies of amino acid composition and lipid profile confirm the high quality and nutritional value of fish protein hydrolysate. The food, pharmaceutical, agricultural, cosmetic, and nutraceutical industries commonly use protein hydrolysate. It could be employed as a protein source in diets for aquatic organisms and other farmed animals [23]. Finally, the solid material from enzymatic hydrolysis can be used as a fertiliser [24].

Natural pigments

Fish and aquaculture products have a diverse range of colour, which influences customers' decision to purchase them. One of the most important sources of natural carotenoids are shrimps and prawns. The increasing production of these types of seafood generates large quantities of processed industrial waste. The yellow, orange and red colour of the shell, skin, and exoskeleton of sea creatures is caused by carotenoids, one of the most commonly known natural pigments.

It is also present in yeasts, all green plants, bacteria, many animals and has various functions [25]. For humanity, the most important aspects of carotenoids are colour and their impacts on food and environment.

Carotenoids could be obtained from industry waste after shrimps, crabs, trout, lobster, crayfish, salmon, snapper and tuna processing. The pricing or grading of seafood is directly connected to the intensity of its red hue. Head and body carapace and the rest of shrimp waste are used for carotenoids extraction with different organic solvents such as methanol, isopropyl alcohol (IPA), hexane, ethyl acetate, ethyl methyl ketone, ethanol, petroleum ether and solvent mixtures like IPA and hexane or acetone and hexane at diverse extraction conditions [26]. Many directives instruct which colorants are safe for the food industry, what sources could be used for obtaining a particular colorant, what solvents might be applied and what purity degree of the pigment can be expected. Colorants are added to make food and drinks more attractive and to improve their stability [27].

The level of environmental awareness is still growing, more and more consumers avoid foodstuff containing synthetic colourants, which forces food industries to use natural pigments. Shrimps waste is a significant source of natural pigments, which could be applied in various products.

Collagen

Collagen is one of the most abundant proteins present in all living organisms and comprises nearly 30% of total protein content. This fibrous protein is responsible for the physiological functions of tissues in skins, bones, tendons and cartilages. Collagen has many applications in the food, cosmetic, pharmaceutical and biomedical industries. The commonly used gelatine is collagen that has been irreversibly hydrolysed. The popularity of collagen results from its excellent biodegradability, biocompatibility, and weak antigenicity [28]. Collagen is isolated mostly from by-products from animals, such as pigs, cows and poultry. Unfortunately, the high price severely limits its use, and there are also problems with sources of collagen according to religious beliefs such as those that forbid pork or cow by-products.

Aquaculture waste processing is a promising source of collagen, which reduces the costs of production and has a positive impact on the environment. Additionally, this type of an alternative source solves the problem with religious beliefs. Preparations of collagen from aquaculture by-products could satisfy kosher and halal requirements [29]. The increasing attention to fish industry waste (skin, scale, bone and others) is due to its high quality of collagen and its ability to serve as a good substitute for mammals.

Collagen from fish waste processing is generally obtained by the methods mentioned and described below:

- Acid and alkali extraction:

The skin prepared for the process is mixed with sodium hydroxide to remove proteins which are not collagenous. The skin is deproteinized and then demineralized using hydrogen chloride. The demineralized skin is then swollen by mixing the skins with acetic acid. After these processes, the skin is mixed with distilled water for various times and at different temperatures. Collagen is obtained from the mixture using filtration.

- Acid and enzyme extraction:

The scales and bones are soaked in sodium hydroxide. The insoluble substances are extracted with acetic acid. Centrifugation of the solution, sodium chloride addition and dialysis against acetic acid result in collagen obtainment. This method takes a long time (near 200h) and requires a large amount of chemicals.

- Extrusion cooking

The key parameters in this method are high temperature, short reaction time and high shear force. Many reactions take place during the extrusion process, such as protein denaturation, gelatinization, hydrolysis of protein, grinding, mixing, shearing, hydration, shaping, partial dehydration, expanding, texture alteration, destruction of microorganisms and other toxic compounds. Collagen extracted from fish scales has a weaker odour than from fish bone and skin. Fish scales consist of collagen and hydroxyapatite, which are tightly linked together [30] and are difficult to separate [31]. The extrusion–hydro-extraction process utilizes the typical extrusion which decomposes the intimate linkage between hydroxyapatite and collagen and simplifies the release of collagen from fish waste extrudes using water extraction. Extrusion cooking is an easy operation that requires little labour and costs and offers continuous production, high yield and multiplicity of products [32].

Fish processing waste clearly has potential to be an alternative source of collagen. It is characterized by high physicochemical functionalities and could be used in various applications, but increases economic returns for the fishery branch.

Chitosan

According to the great diversity of aquaculture waste, different types of disposal could be used in various applications. Shellfish by-products, which consist of crustacean exoskeletons, constitute the main source for chitin production. Chitin is a polysaccharide, which contains N-acetyl-D-glucosamine units. It is a specific component of the cell walls of fungi, the exoskeletons of crabs, lobsters, shrimps, insects, as well as the beaks and internal shells of cephalopods [33]. There is currently a high interest of chitosan, a deacetylated derivative of chitin. Chitosan has many biological properties, such as anti-cancer, antioxidant, and immune-enhancing and thus can be applied in various ways [34].

Present-day polymers are mostly synthetic materials, which are not as biodegradable as the environment's opportunity to degrade. Natural polymers are a bio-replacement for a portion of synthetic polymers [34]. Chitosan has relevant properties such as non-toxicity, biodegradability, biocompatibility and adsorbability [35].

Other useful features of chitosan are anti-bacterial properties [36]. These parameters make chitosan a suitable functional material that could be used in food, biomedical, cosmetics and pharmaceutical applications [37]. The most popular processes using chitosan are binding, thickening, gelling, and stabilizing.

The multidimensional utilization of chitosan in the medical, cosmetic, food, and textile industries requires the development of extraction methods [38]. Isolation of chitin from shellfish waste and conversion of chitin to chitosan require the following steps:

1. Demineralization - calcium carbonate and calcium phosphate separation
2. Deproteinization - protein separation
3. Decolorization - removal of pigments
4. Deacetylation – removal of acetyl groups.

To remove some or all acetyl groups from the chitin and obtain chitosan, the process should be conducted with a concentrated sodium hydroxide solution at high temperature [39]. Many studies have proved that the physicochemical properties of chitosan depend on preparation methods, crustacean species, temperature, autoclaving, and concentration of sodium hydroxide solution.

Marine biowaste processing is the main source of chitosan, but chemical extraction with existing methods is wasteful and expensive. To produce one kilogram of chitosan from shrimp shells, more than one tonne of water is required. Due to costs, legal restrictions and environmental problems, many studies have been conducted to make chitosan production profitable, sustainable and environmentally friendly. Fortunately, new technologies are emerging. Methods using bacteria to prepare chitosan from aquaculture waste minimize environmental pollution [40]. Physical and solvent-free methods for shell fractionation should be available in the next decade.

Advantages and disadvantages of described methods

Table 1. Advantages and disadvantages of described methods

Type of utilization of aquaculture waste	Advantages	Disadvantages
Fish Biogas	• Renewable energy source and cost efficient tool to approach greenhouse gas reduction • Cheap recycling of organic waste that could be harmful to human existence • High content of organic carbon in fish waste effect on high methane potential • Ability to co-digestion • Odour regulated production • Regulated pathogen and diseases vectors e.g. flies in fishing ports [41]	• High content of ammonia nitrogen in fish waste limits biogas production • High investments costs involved in building biogas plant
Biofertliser from fish waste	• Cost effective, eco-friendly product for agriculture • Complete fertiliser contains all the essential minerals • Dramatic stimulation to the soils beneficial microorganisms which consume, digest and release the abundant nutrients in the fish when it is applied to the soil. • Amino acids present in 'Fishlizer' will enhance flowering and fruit setting in plants, favoring enhanced production. [42]	• The composition of fish fertilizers is variable. • Risk of infections • Effectiveness deepened on Moisture, temperature, pH and other environmental variables. • High transportation and labor costs
Fish Bio-oil/biodiesel	• High quality biodiesel • Larger acid number, a greater increase in the rate of peroxidization	• Higher emission of oxides of nitrogen • Generally higher production cost

Type of utilization of aquaculture waste	Advantages	Disadvantages
	with the increase in the time that it was stored, greater kinematic viscosity, higher heating value, higher cetane index, more carbon residue, and a lower peroxide value, flash point, and distillation temperature than for e.g. cooking-oil biodiesel If produced chemically: • high conversion • ratio of triglycerols (TAG) to methyl esters (biodiesel) • low reaction times (4-10 h). If produced enzymatically: • there is no soap formation, • low temperature requirement, • no waste generation • high quality of glycerol [43]	• Less oxidation stability than diesel [44.] If produced chemically: • high reaction temperature, • soap formation, • waste generation and contamination of glycerol with alkali catalysts. If produced enzymatically: • high reaction times (12-24 h) high cost of enzymes
Fish protein hydrolysate	• Highly nutritious and easily digestible • Wide range of applications as milk replacers, stabilizers in beverages, protein supplements and flavor enhancers If produced chemically: • High recovery yields • Fast process • Inexpensive process If produced enzymatically: • Higher nutritive value and functionality • High recovery yields • High selectivity • Low-salt final product • Low contamination of wastes	If produced chemically: • Complete destruction of tryptophan and cysteine and partial destruction of tyrosine, serine and threonine • Difficulty in process control If produced enzymatically: • Bitterness • High-cost enzymes (except autolysis) • Long-time process • Potential decrease of protein functionality [43]
Natural pigments	• Great variety of colours in aquaculture waste • Carotenoids from shrimps have low impact on food and environment	• Higher price than artificial pigments • Lower quality than pure synthetic pigments
Fish Collagen	• Fish collagen peptides have best absorption and bioavailability due to their smaller particle sizes compared to other animal collagens • Type I collagen - best source for medicinal purposes • Tasteless and odourless or have a neutral, non-fishy taste.	• Contains allergens for users with allergic to fish
Chitosan	• Chitosan from shellfish by-products is the most commonly available • Methods using bacteria to prepare chitosan from aquaculture waste minimize the environmental pollution	• Chemical extraction with existing methods is wasteful and expensive • Properties of chitosan depend on preparation methods, crustacean species, temperature, autoclaving, concentration of sodium hydroxide solution

Source: Author's

Summary and conclusions

In the future, the aquaculture sector will need to produce more with less. This means an effective usage of resources, growing earnings and sustainability practices on the one hand, and on the other hand inputs, pollution and waste reduction. Different types of aquaculture waste could be treated with various methods. The conversion of non-recyclable fish waste materials into biogas, biodiesel and biofertiliser is the most appropriate method for sick or dead fish and mixed waste processing. Additionally, the hazardous biomass is recycled and converted to usable heat, electricity, or fuel. Waste, which consist mostly of fish viscera, has the biggest potential to obtain protein hydrolysate. Among the most prominent current uses of aquaculture waste are pigments, chitosan and collagen isolation for cosmetics, food, biomedical and pharmaceutical industry. Energy recovery and obtaining the essential compounds from aquatic waste need extra inputs and outputs of the various activities involved in waste processing. The development and industrial implementation of the best alternative treatment process for specific type of waste should predate lab-scale evaluation. However, it is important to estimate the benefits of processes not only in terms of economic income, but also considering the environmental impacts. Recycling and processing of fish by-products play a key role for marine resources conservation.

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INFLUENCING THE COMMERCIALIZATION OF INNOVATIVE RESEARCH RESULTS IN UNIVERSITIES OF ECONOMICS AND BUSINESS

Abstract
The majority of knowledge and technology transfer models relate to universities of technology and natural sciences whose commercialization potential allows them easily to adapt their outcomes to market demands. This, however, is not the case for universities of economics and business. Therefore, the aim of this paper relied on systematic literature studies performed with the use of a snowball sampling method. It was followed by an empirical study comprising nearly 60 in-depth interviews, 20 innovation audits and seven intellectual property valuations in Special Purpose Entity of Poznan University of Economics and Business. The study attempts to fulfil a research gap concerning the role of business schools in the commercialization of scientific research in Poland and other CEE countries.

Key words
knowledge management, knowledge commercialization, knowledge transfer, innovations

Introduction

The traditional Humboldt university model in which institutions of higher learning are focused predominantly on teaching and research is undergoing a revolution driven by the rapid advances of globalization, technology and today's economies. Universities are subject to far-reaching changes as they evolve from government-funded scholarly institutions into international know-how centers, frequently referred to as third-generation universities or 3Gus, as well as entrepreneurial universities [1]. According to Wissema [2], the new model of institutions of higher education aimed at commercializing research outcomes with the support of technology startups, technology-based companies and institutions which finance their operation, has become indispensable for scientific progress.

In recent years, growing interest in university-industry knowledge transfers has prompted a heated debate on the model that universities would be best advised to adopt and the activities they should pursue to promote effective engagement with industry and society at large [3]. Many scholars who studied university-industry connection mechanisms have argued that research collaborations are extremely important mechanisms for generating academic spillovers. Therefore, works by Etzkowitz and Leydesdorff [4, 5] on the Triple Helix Model (THM) followed by Quadruple and Quintuple Innovation Helices proposed by Carayannis and Cambell [6, 7] about interaction among university, industry, as well as government are the key to innovation and growth in a knowledge based economy.

Without a doubt, universities play an invaluable role in innovation systems. The importance of universities third mission support is included in the EU strategic documents, such as "Higher Education and Regions, Policy Brief" by OECD [8]. Korpysa [9] asserts that the spin-off companies he has studied are pursuing the Schumpterian model of entrepreneurship, in which knowledge and business opportunities are employed to bring new solutions to market. However, universities' ability to create new knowledge and deploy it for economic benefit hinges on an array of economic, legal, social and political factors. Many additional internal influences arise within universities that determine the rates and directions of knowledge flow from that institution [10].

In view of the misgivings that have been identified, the article sets out to outline the factors that affect research outcome commercialization. The publication also attempts to respond to the problem presented by Wright and associates [11] regarding the role of business universities in the commercialization of research outcomes. Such commercialization was in the focus of nearly 60 in-depth interviews, 20 selected innovation audits and seven intellectual property valuations at the Poznan University of Economics and Business conducted in the run-up to the establishment of a Special Purpose Entity.

The article also refers to observations by Gál and Ptaček [12], who relied on a study conducted in Hungary and the Czech Republic, to demonstrate the need for developing knowledge transfer models dedicated to universities in post-communist countries. Hence, in view of similarities in the economic and social environments, the examples quoted in this article may provide inspiration for other faculties of economics in Central and Eastern Europe.

Literature review

The literature on university-industry interaction usually displays patenting, licensing and formation of start-up companies as the main determinants of successful technology diffusion [13]. Shane [14] points out the importance of academic entrepreneurship, such as companies that form from university spin-offs in the commercialization process. According to Clarysse et al. [15], the number of academic spin-offs is accelerated by the ownership of intellectual property rights by technology transfer offices (TTOs), the pressure on universities to commercialize their research, as well as the support of public funds, as Fini et al. [16] confirmed. However, some authors suggest that publications, conferences, informal interactions and consulting [17], as well as formal arrangements such as contract research or joint research agreements [18] and personnel mobility, informal contacts or consulting relationships [19], are of greater importance. Perkmann and Walsh [20] summarize the university-industry links as research partnerships, research services, academic entrepreneurship, human resource transfer, informal interaction, commercialization of property rights and scientific publications.

Also, the latest publication on public policy measures designed to support knowledge transfer activities, which was based on a literature review [21], has identified a knowledge gap. As described earlier by Rasmussen and Rice, the reason the knowledge gap formed is that academic researchers and entrepreneurs lack the managerial skills and competences needed to advance their technologies or start-ups to a point at which successful negotiations with industrial partners or external investors may be conducted [22]. Carayannis and Dubina also point out the importance of intellectual capital and sustained investment in people as the main factors for the quality of innovation in smart, sustainable and inclusive growth [23].

Likewise, research by Boh, De-Haan and Strom [24] has shown the importance of business education in leveraging all potential university resources for technology transfer. According to the authors, entrepreneurship programs allow universities to leverage their own assets, bridging gaps between public funding of basic research, private funding of applied research, and research commercialization efforts. These programs are consistent with the universities' missions to educate, as well as to create and disseminate knowledge.

In view of the above observations, the main research question of this article is what role universities of economics and business are playing in the knowledge transfers that are believed to contribute to the development of a knowledge-based economy.

According to Suddaby and Greenwood [25], one of the functions of Business Schools should be to produce new managerial knowledge and circulate it by educating students and providing them with a common language, shared analytical tools and a unified set of assumptions. Starkey and Madan [26] argue that business schools can mainly develop academic entrepreneurship and entrepreneurial competencies in universities. Wright et al. [27] see the direct and indirect role of roles of business schools as providing tools, such as courses on entrepreneurship or doing research "on barriers at systematic level to the development of companies from universities" or directly by providing resources, such as by acting as directors on the boards of spin-off companies.

Wright and associates [11] have prepared a case study based on 42 in-depth interviews with representatives of technology transfer centers, deans of business schools and research and teaching faculty members at eight UK-based institutions of higher education. They examined the challenges to the role of Business Schools in promoting academic entrepreneurship. Their findings suggest that the institutional structures of universities restrict the role that Business Schools may play in addressing knowledge gaps in the development of academic entrepreneurship. Institutional structures hinder interactions between the different stakeholders of academic entrepreneurship, and interactions with Business Schools in particular.

However, Khurana [28] emphasizes that university business schools have not been immune to the growing pressures to make scholarly knowledge more impactful and commercially relevant, nor have they been saved from sharp criticism about the intrusion of market imperatives in business and management education. Although management scholars seldom produce results that can be embodied in physical products as in the case of engineering or medical research, their research occasionally yields outputs in the forms of designs, methods, rules, tools and instruments that can be commercialized similar to any other technology. Such is the fundamental assumption underlying the importation of the technology transfer approach into the realm of administrative sciences [29].

The above recommendations are crucial for the development of the unique dynamics of Central and Eastern Europe (CEE). Since the enlargement of the European Union in 2004, the combined GDP (Gross Domestic Product) of CEE countries increased by nearly 80%, while the economic strength of the old EU countries rose by a mere one fifth. In 2013, Poland, which undoubtedly plays a leading role in Central and Eastern Europe, accounted for a 35% share in the total GDP of all Central and Eastern European countries. Although the growth rate declined somewhat in recent years, the CEE region holds a continued appeal to investors from all over the world [30].

According to the 2013 World Bank report, Poland ranks as the largest economy of all post-socialist EU member states and the sixth largest in the European Union in terms of purchasing power parity. Moreover, Poland has just experienced what appears to have been the two most prosperous consecutive decades in its history of more than a thousand years. Economic growth models tend to underestimate the unprecedented headway that has been made in improving the quality of education. As of today, nearly 60 percent of Poland's young adults (aged 18-24) are enrolled in tertiary education – this represents the second highest ratio among the OECD (*Organisation for Economic Co-operation and Development)* countries [31].

Given the current state of play, the challenge faced by Poland's universities is to create an ideal model of cooperation between science and business to fill the existing innovation gap in Poland's highly dynamic economy by fostering entrepreneurship education. Businesses and economic universities play a central role because according to Poland's Central Statistical Office (2013/2014), the country is currently home to over 70 higher schools of economics, including universities, and business and administration programs enroll more than 20% of the country's entire student population. Supplementary research questions are how and by what methods can we determinate the commercialization potential at business universities?

Research methods

The research methodology proceeded in two stages. Stage one incorporated a detailed literature review covering the available electronic databases such as Google Scholar, Scopus and the holdings of the library of the Poznan University of Economics and Business. Articles for the review were selected by a snowball sampling method that limits the percentage of articles collected at each level [32]. English and Polish-language writings were selected using the keywords "knowledge management", "knowledge commercializatio", "knowledge transfer" and "innovations". The inclusion criteria were studies that focused on business and economics schools and universities. The literature search generated 63 papers that were retrieved for more detailed evaluation and enabled the formulation of the research problem [33].

The second stage assessed the commercialization potential, skills and competencies of the Poznan University of Economics and Business research teams from 2010 to 2013. The assessment methodology was based on a thorough literature review comprising four phases consistent with the common schedule of technological audits, i.e.:

1) opening,
2) data collection,
3) result analysis and synthesis,
4) report drafting and handover [34].

Table 1. Data collected before innovation audits at Poznan University of Economics and Business

Faculty	**Research grants and project in years 2010-2013**		**Doctorates in years 2010-2013**		**Habilitations in years 2010-2013**	
	total	analyzed	total	analyzed	total	analyzed
Faculty of Economics	2	2	51	0	13	3
Faculty of International Business and Economics	2	2	23	1	6	3
Faculty of Informatics and Electronic Economy	6	5	20	1	6	5
Faculty of Commodity Science	5	5	21	4	6	4
Faculty of Management	12	10	56	2	19	10
Total	27	24	178	8	50	25

Source: Author's research

Phase one involved a series of 57 individual and group interviews with the research teams of the Poznan University of Economics and Business, representing all faculties of the university. Note that the faculties vary widely in their profiles, ranging from the strictly economics-oriented Faculty of Economics, to the highly management-focused Faculty of International Business and Economics and Faculty of Management, to the Faculty of Informatics and Electronic Economy that specialize in economic IT, and the interdisciplinary Faculty of Commodity Science. The respondents were selected based on a study of the university's research grants and projects, as well as a list of first (doctoral) and second (habilitation) degree dissertations completed between 2010 and 2013. Table 1 summarizes data collected for each department.

The commercialization potential of current research was assessed and described based on 57 meetings in a document entitled "The Project's Commercialization Potential Identification Form". The document addresses the following four questions:

1. To what extent are the research outcomes likely to attract the interest of domestic businesses?
2. What advisory services may be offered based on the research findings?
3. What training may be offered based on the research findings?
4. To what extent is the project suited to encourage businesses to engage in research collaboration?

At this stage, the survey form and the scope of the report have been modified to fit the concerned report and to select and approve the auditors [35].

Preliminary analysis of the commercialization potential involved data gathering. On that basis, the authors selected 20 projects for an innovation audit. According to the university's profile, opinions on the commercialization potential were divided into two categories: opinions on solutions (9 audits) and opinions on technologies or products (11 audits). The technology reports briefly describe the technology focusing on its innovation and market potential, roughly analyze the target market, including its scope and growth prospects, and identify competition and barriers to entry, intellectual property protection status and research team profile. They also suggest ways to continue developing the technology, with an eye to furthering specific deployments and provide guidelines on how to formulate proposals.

The solution reports contain descriptions of individual solutions, including their nature and business value. They also describe the market in terms of the availability of comparable services/solutions, analyze the structure of service/solution proposals, outline consultant team profiles, offer recommendations on deployment stages, schedules and possible forms of intellectual property protection, name parts of the solution/service requiring protection and identify the university's activities designed to ensure the proposals are unique. The innovation audits were conducted by several internal and external auditors with experience working at an institution of higher education as well as in industry, including in the field of technology transfers [36]. Every meeting with the audited research organization was additionally attended by a member of the project team representing Poznan University of Economics and Business. For each meeting, the results were described in either a solution sheet or a technology sheet containing the most essential evaluation points.

The audit reports focused on areas in which commercialization opportunities were identified. For each area, existing and potential opportunities were defined and possible actions proposed [34].

The next step was to value any intellectual property (knowledge and technologies) in the possession of Poznan University of Economics and Business that has been in demand in the business community. The purpose of the exercise was to assess the knowledge and technologies held by the university. Such valuation was limited to the seven projects endorsed by experts during their preliminary analysis, which underwent innovation audits and were sought by industry practitioners, such as via the website. Most projects came from the interdisciplinary Faculty of Commodity Science.

One of the outcomes of this effort was a report on the valuation of the intellectual property of Poznan University of Economics and Business, which specified the purpose of the valuation and described the valuation method. The adopted method was income-based, in keeping with recommendations which, in the opinion of the Ministry of Science and Higher Education and the National Research and Development Center, may and should be used by State Research Institutions[1]. The method was also market- and cost-based.

Other results included the formulation of precepts for and the adopted definitions of the discount rate, the rationale behind method selection, a description of the technology based on the technology potentials sheet, an interview with the authors, and a market description, including a basic SWOT analysis for the technology and for barriers to market entry, and descriptions of basic market players. Such players include a list and a short description of companies listed in market and patent databases, commercialization paths, and the recommended path for the technology in question. The recommendation/choice and an assessment of the technology by the selected method was made in keeping with the recommended commercialization path.

Results and discussion

The knowledge generated by universities, especially those oriented toward economics, may form an important launching pad for commercializing innovations [37]. However, the nature of university-industry collaboration has changed during the last decades, and it varies across countries and regions [38].

Therefore, this paper introduces the role of business schools in knowledge transfers, since only limited literature is available. Moreover, the commercialization of research outcomes in universities of business administration and economics requires a proper dedicated model. Universities in post-communist countries play a lesser role than those of more developed EU countries, as adaptations to new social and economic conditions in the former began substantially later than in Western Europe [12].

The literature emphasizes the importance of enlisting teaching and research faculty members to serve on the boards of newly established enterprises and, even more importantly, having them contribute in an advisory and consulting capacity. Hence, the research faculty of universities of economics should engage in the work of technology transfer centers and fill their knowledge gaps [11].

Locke [24] notes the potential to offer entrepreneurship courses for graduate and doctoral students taught by practitioners, as well as university teacher courses in marketing, law, economics and finance. These may prove to be of particular value for the establishment or continued development of startups. Universities of economics should assume the role of teaching managerial knowledge [25, 41].

Note that Arvanitis and associates [41] have found that institutions of education specializing in economics and natural sciences were the most dedicated to transferring knowledge and technologies. Therefore, the aim of the current research was to achieve a better understanding of the knowledge transfer process in those institutions based on 57 in depth interviews, followed by 20 innovation audits as well as seven selected project valuations at PUEB (Poznan University of Economics and Business).

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[1] As presented in the guidebook entitled “Komercjalizacja B+R dla praktyków” (“R&D Commercialization for Practitioners”), Warsaw, 1st edition of 2010 and 2nd edition of 2013, p. 171 and p. 187, respectively.

According to Bell et al. [36], technological audits of universities are aimed at: 1. assessing the potential to boost the revenues of universities at large and their individual departments by utilizing the available technologies and equipment, as well as the knowledge contributed by research staff; 2. identifying the sources of strategy information to be used for management purposes at various levels; 3. incentivizing employees and enhancing their "industry awareness".

Defined in such a way, the commercialization of research outcomes has become the centerpiece for assessing the commercialization potential of Poznan University of Economics and Business. The assessment relies in part on identifying research outcomes and, as a consequence, evaluating their attractiveness:

- based on research papers and abstracts (assessment of the potential value of specific topics and possible applications),
- based on patent databases (leading centers, growth objectives),
- against existing business offerings (market saturation, key advantages),
- in terms of application potential (declared interest).

Note that the proposed technology identification procedure, which complies with the "Rules governing the management of copyrights, related rights and industrial property rights and commercialization at the Poznan University of Economics and Business", accounts for the university's economic profile and clearly distinguishes between research on the commercialization potential of patentable or licensable technologies and research on solutions which hold no such promise. Applying such a procedure might help the long-term strategy of commercializing selected intellectual property generated at the PUEB and comprising either technologies or knowledge. The PUEB envisions the valuation and commercialization of successive future solutions.

However, the SPE (Special Purpose Entity) of the PUEB supports scholars in deploying their research outcomes and, contrary to technical and natural science universities, does not limit itself to assisting in the acquisition of patents or the conclusion of license agreements. Markiewicz [42] defined the commercialization of research outcomes as actions aimed at constructing a business model of technology, designing the sales process or bringing technologies to market. Generally, such commercialization is about ensuring that items of potential value and having the capacity to generate profit are sold, produced, made available or used for profit, to produce capital or create added value by means of the technology in question.

Based on 57 in-depth interviews at Poznan University of Economics and Business, highest commercial potential was observed at the Faculty of Commodity Science, followed by the Faculty of Informatics and Electronic Economy, as well as the Faculty of Management. Hence, out of 20 innovation audits, 45% (9 audits) were selected from the Faculty of Commodity Science, 25% (5 audits) from the Faculty of Management, 20% (4 audits) from the Faculty of Informatics and Electronic Economy, and only 1 audit (5%) from the Faculty of Economics and the Faculty of International Business and Economics.

Thus, assessments of the university's innovation and overall potential are expected to generate tangible financial benefits through deployments [43]. Such assessments will also enhance the commercialization process achieved by assessing the commercialization potential of innovation, drafting commercialization business plans and acquiring external financing for the commercialization of innovations. In this field, the SPE relies on basic business theory and, as such, helps formulate the vision and mission, proposes values and designs the business model [44].

Founded on an analysis of project outcomes, 20 industry-targeted offerings of the PUEB were selected and posted on the http://scuep.pl/ website. The website made it possible to search and commercially apply research outcomes, new concepts, ideas, and inventions, thereby making the PUEB more advanced and competitive. The website is particularly geared towards businesses and business support institutions, including research and development centers, deployment institutes, public authorities, as well as advisory, training and consulting organizations. The website was used to submit to Poznan University of Economics and Business more than twenty inquiries regarding joint research collaboration, consultations and training.

The research also helped delineate the new commercialization pathways of research at the economic university in the form cooperation on projects conducted by interdisciplinary research teams by identifying and assessing the commercial potential of the research teams of the PUEB and boosting their knowledge and skills. Such a multidisciplinary approach has led to the emergence of a thriving literature on technology transfers featuring insights contributed by entrepreneurs, economists and managers [45]. These findings also complement previous observations by Olmos-Peñuela et al. [46], who investigated social and humanities research groups' engagement in knowledge transfer.

Furthermore, emphasis has been placed on engaging not only the university's research and teaching staff, but also its students in the commercialization process. The effort is in line with recommendations published by Grimaldi et al. [47] and Boh et al. [24], who stressed the key role of students (mainly of business majors) at early stages of spin-off development. Research on entrepreneurship among students also held Kopycińska et al. [48] compare Polish, Lithuanian, Latvian, Hungarian, Ukrainian and Russian experiences, as well as by Tho and Trang [49] who worked with business students in Vietnam.

According to Paton et al. [50], university business schools contribute best to the practitioner world, not by meekly acceding to the latter's pressing demands but by working alongside in a strategic partnership where each recognizes the strengths of the other for what they can really do. Once the business potential of universities of economics in the countries of Central and Eastern Europe to commercialize research outcomes has been tapped, further research opportunities are certain to emerge.

Presented findings suggest some recommendations and policy implications. First, the commercialization of research at business universities should be accompanied by continuous monitoring of the commercialization potential through innovation audits. Such research primarily highlights actual problems and needs, but also provides information that can be used in action plans for improving performance. Such audits also open opportunities for exploring alternative uses of university-based knowledge through consulting, combining interdisciplinary knowledge in different teams or engaging students in research projects. Second, literature studies pointed to the great potential of economic universities in teaching entrepreneurship and entrepreneurial competencies, as well as developing academic entrepreneurship.

Conclusion

The overall purpose of the article was to point to selected factors for the commercialization of research by using a snowball sampling literature studies method, as well as describing the case of Poland's universities of business and economics. The emerging science and industry collaboration model designed for universities of economics was the procedure – described extensively in the literature – of assessing innovation potential by conducting innovation audits and valuations. For the purposes of the study at hand, such audits and valuations were modified to fit the specific needs of universities of economics. Furthermore, the study helped set out further growth objectives for the newly-established Special Purpose Entity of Poznan University of Economics and Business.

The paper also attempts to fulfill the research gap concerning the role of business schools in the commercialization of scientific research in Poland and other CEE countries.

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A REVIEW OF MECHANICAL PROPERTIES OF DIAMOND-LIKE CARBON COATINGS WITH VARIOUS DOPANTS AS CANDIDATES FOR BIOMEDICAL APPLICATIONS

Abstract
In the modern world, there is an increasing demand for implants, and technologies connected with their manufacturing. One of the possible paths of their development relates to the use of diamond-like carbon coatings (DLC) for the improvement of surface properties of the biomaterials used for implants. Further improvement of the mentioned properties can be induced by means of doping of the coating. Among the elements which are under current investigation of researchers, the following can be placed: Ag, Si, F, Cu, Ti, Ca and P. This paper reviews previously published experimental data concerning mechanical and physicochemical properties of DLC coatings doped with Ag, Si, Cu, Ti, Ca, F and P as candidates for biomedical applications. Although plenty of articles are published in the mentioned field, the differences of coatings' synthesis techniques, various sources of dopants and substrates, as well as conducted experiments make no consistent view about a possible solution for their future implementation in medicine. Some of the selected dopants (Cu, Ca, P), still require better characterisation of mechanical properties. There is a necessity to conduct studies of mechanical and physicochemical properties of DLC coatings doped with these elements. This will enable adjustment of the necessary technological parameters to biomedical requirements.

Keywords
Diamond-like carbon, doping, mechanical properties, thin films, biomaterials

Introduction
Modern world could not exist without a continuously developing health care system. Implants of various assignments, from bone stabilizers and prosthesis to peacemakers or artificial organs are in common use. Market requirements in that field are still growing both in case of number, as well as functionality of implants. Only in the case of orthopaedic surgeries, increasing demand for implants inserted each year is well visible. In USA, the annual increase of total hip and knee arthroplasty declared for 2010 was estimated to be on the level of 4.3% [1], while in England and Wales between 2008 and 2010 the number of such treatment increased from about 110 000 to 166 000 [2].

One of the crucial aspects of an interaction of a biomaterial with a tissue is through its surface. Both initial and long-term responses to a grafted material depend to high extent on its surface properties. Some of the main problems to overcome are unfavourable biological phenomena like those connected with the release of metal ions from the implant to the surrounding tissue leading to their deposition in tissues and organs (spleen, liver, blood, etc.), allergies or tissue irritation [3]. For this purpose, the use of biocompatible coatings seems to be a reasonable solution. The rapid development in this field concerns mostly the use of diamond like carbon (DLC) coatings. These coatings act as a diffusive barrier preventing tissue near implantation site from the penetration of metal ions [4,5,6,7]. What is more, since carbon itself possesses a biocompatible character, it ensures the biocompatibility of the whole coated material. Recent studies moved even one step further. Through doping of DLC with various elements, new biologically significant features were obtained. Among dopants that have a high potential for improving the properties of coatings for implants there are: Ag, Si, Cu, Ti, Ca and P [8]. By the addition of Ag and Cu, the risk of post-operational complications involving yeasts or bacterial infections was reduced [9]. In the case of presence of Si and Ti in DLC coatings, the improved osteointegration of implant with host tissue was observed [10,11]. The aspect which is very important for cardiovascular grafts is prevention of clot formation. Such effect was observed for example using Ca, P or Si as a doping material [12,13].

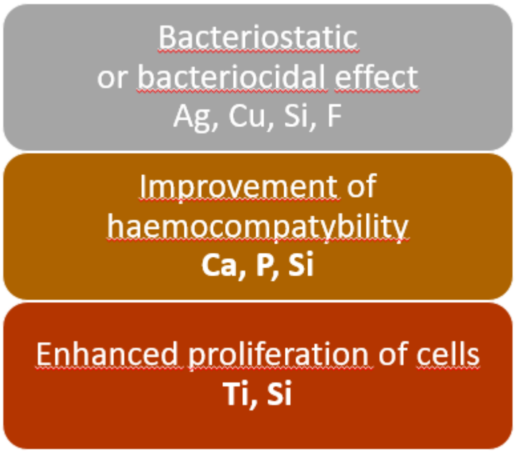

Fig. 1. Dopants of DLC coating for potential biomedical applications
Source: Author's

Although high impact was placed on the biological evaluation of the mentioned coatings [8,14], it should be remembered that even the best bio-features will not secure the success of the end product without appropriate mechanical and physicochemical properties. Living body is in fact a very hostile environment. Implants are in constant contact with severely corrosive biological solutions and body fluids. In orthopaedics, implants are commonly working under load-bearing conditions, where good adhesion of the coating and its wear resistance are crucial, otherwise wear debris become even more dangerous for the patient's health than the implant itself. Moreover, the proper mechanical properties are required not only during the initial stages of health treatment, but starting from the implantation process until the end of the patient's life. Considering the above, due to an increasing life expectancy of the population, the need of a fail-safe implant life span is also rapidly increasing.

There are already several published reviewing articles concerning undoped DLC coatings or focusing only on few of the doped derivatives [14-16]. In some publications, authors consider mostly only one aspect of DLC coatings, like their biological [8] or tribological properties [17]. The purpose of the present paper is to evaluate mechanical and physicochemical properties of DLC coatings doped with Ag, Si, Cu, Ti, Ca and P, i.e. the elements that can positively influence their potential for biomedical applications according to biological evaluation.

DLC Coatings

One of the commonly used generalizations is that DLC coating is build up as amorphous carbon with some sp3 bonds contained in its structure. In fact, this name stands for an entire range of various coatings with different ratios of sp2/sp3 fractions. What is more, differences in the hydrogen level in these structures are very high. In the literature, three abbreviations: ta-C, a-C and a-C:H, are typically used. The first one stands for tetrahedral amorphous carbon, a structure resembling diamond, and as a result – possessing the highest sp3 content. In the second case – the amount of amorphous carbon with a planar sp2 configuration is on the level close to sp3, and lays in the range of 20 to 60%. The last option covers the coatings with a high amount of hydrogen, which is usually related to the presence of higher amount of sp2 bonds. The type of obtained DLC is highly dependent on the manufacturing technology [2,15], which at the same time provides different coating properties of such as different internal stresses or coefficients of friction [13,18].

The common drawbacks of DLC coatings are: high internal stress [16,18,19] and degradation of mechanical properties due to heat treatment [20]. It should also be remembered that because of high internal stresses, an additional problem concerning coating's delamination may appear. There exists a relation between the level of internal compressive stress and the sp2/sp3 ratio. It shows that the presence of high amount of sp3 bonds in the material (above 80%) leads to higher stress values that can even reach 10 GPa [22].

Influence of synthesis method and process parameters on DLC properties

In the beginning of 70s, the first studies leading to synthesis of DLC coatings were conducted with the use of ion beam deposition by Aisenberg and Chabot [23]. From that time, various techniques including magnetron sputtering, laser ablation, chemical vapour deposition etc. were investigated. The mechanical and physicochemical properties of synthetized DLC coatings depend both on the process parameters and the production technique itself [15,16]. Trava-Airoldia et al. [26], showed that a significant difference between hardness, tribological properties, total internal stress and adherence of DLC synthetized by r.f. PACVD, IBAD, and Enhanced Pulsed-Direct Current PECVD (EP-DC PECVD) appears, even if all manufactured coatings are of the same thickness. The mentioned coating properties were described as a function of self-bias voltage, ion beam current, and pulsed-bias, respectively for each method. Although in all cases Raman spectroscopy revealed an increase of ID/IG ratio with the increase of self-bias and ion current, the degree of graphitisation of the coating varied among the techniques. In the case of evaluation of total compressive stress of DLC, the highest value of that parameter was usually obtained for intermediate process parameters (voltage bias or current). The lowest compressive stress was obtained for the highest negative voltage bias in case of PACVD method and highest current of IBAD processes, but lowest negative voltage bias in EP-DC PACVD method. The exact values of stress differed from about 0.5 up to 3 GPa [26]. The influence of the substrate material on the evaluated compressive stress was also visible. The difference between stress of coatings synthetized on silicon wafer and Ti6Al4V substrates with an amorphous silicon interlayer was higher than 0.5 GPa. It must also be remembered that the method of coating synthesis also affects the technical aspects of the process, for example different deposition rates, which may differ in suitability for laboratory and industrial scales of coating manufacturing.

In the case of synthesis of DLC by CVD methods, a crucial aspect was also a selection of the carboniferous gas which also could influence the rate of coating deposition [27]. Gases introduced to the chamber could additionally affect DLC deposition by magnetron sputtering. Data presented by Libardi et al. [28] showed that in general, the highest hardness of coatings had been found at approximately 10% of hydrocarbons content. Nevertheless, lower hardness of films was obtained when acetylene was used rather than methane. What is more, gas composition inside the chamber affected surface roughness, which was the lowest for methane/argon mixture. In the literature, DLC roughness was also related with temperature of the surface [29] or impingement energy of ions [30].

Even in the case of processes conducted with the same technique and with the use of the same substrate, DLC coatings could reveal different properties depending on detailed parameters of the synthesis, for instance, in studies concerning synthesis of DLC by radio frequency (RF) magnetron sputtering conducted by Chowdhury et al. [31,32]. In the study, the influence of substrate temperature and of target self-bias voltage on the mechanical properties of the coating were examined. It was observed that not only hardness and Young's Modulus of the DLC layer, but also internal stress and ID/IG ratio were affected.

Doping of DLC

In order to overcome the existing problems with some mechanical, physicochemical or biological properties of DLC coatings or for their improvement, the use of various doping elements and materials is common. In the literature, not less than 26 various dopants of amorphous carbon films can be found [25,31,32]. Studies involving multiple dopants have already been conducted to adjust the DLC parameters to an even higher extent.

In current scientific publications, the following nomenclature is typically used: the dopant atom is written as the first one and is separated from DLC abbreviation by a dash. In case when interlayers appear, they are separated by a slash. However, in many cases the information about the interlayer is given only in a descriptive way.

The introduction of the dopant element is usually performed with the sputtering of the solid target, or vaporization of solid or liquid material. The selection of dopant's source depends to a high extent on the selected method of DLC deposition. In some cases, additional restrictions concerning corrosive or flammable character of some compounds had to be taken into account. The most common approach to DLC doping, both in laboratories and industry, is by the use of sputtering methods or Plasma-enhanced chemical vapor deposition (PECVD). In the first case, techniques were selected mostly due to their simplicity and possibility of using wide range of targets, both conducting and non-conducting. DLC can be synthetized by DC or RF sputtering of graphite [35,36], pyrolitic carbon [37] or even diamond powder [38] in an argon plasma. In some studies, the reactive atmosphere was used. This means that hydrogen or hydrocarbons in a gaseous form were additionally introduced into the chamber during the deposition. The major drawbacks of sputtering methods are relatively low rate of coating deposition (on the level of few nanometers per minute), contamination of targets in reactive processes or concomitant sputtering of several targets of different materials [27,39]. In general, PECVD method requires a formation of plasma between two electrodes. Usually one acts as a table for mounting samples, while the walls of the chamber act as the second one. The precursors of both carbon and dopant elements are introduced in gaseous forms. The major advantage of such technique is the possibility of uniform coating deposition for large areas or complicated shapes. On the other hand, however, selection of precursors could be problematic for all the dopants that should be in a gaseous state or easily evaporative compounds, containing in their structure only element of interest and carbon (so as not to contaminate the coating with an unwanted element). In many studies, also hybrid methods were introduced, which enabled to partially overcome the limitations of each separate technique.

Among the fields of DLC improvements, which are under constant investigation of researchers all around the world, predominantly there are: tribological behavior, adhesion, surface energy, biological response, optical and electrical properties. Low coefficients of friction were obtained mostly by incorporation of F [40] and Si in DLC coatings [41], but also metals like tungsten, especially in presence of high temperatures [42, 43]. One of the common operations to improve DLC adhesion is with the use of interlayers. In this case not only single and multilayers, but also gradient ones were introduced [44,45]. Among the elements responsible for altering the hydrophobic/hydrophilic properties of DLC numerous dopants, both metallic and non-metallic like: Si, F, O or N were used [46]. As far as biological response is concerned, the most important aspects are biocompatibility, osteointegration, haemocompatibility or antimicrobial activity. The electrical resistance of doped DLC did not change linearly with the addition of dopant. This is because DLC can be treated as an amorphous semiconductor. The concentration of additive atoms must be large enough to form continuous channels for electron transport. Introduction of n-type impurity into DLC films (electrons close to conductive band) could improve the field emission performance. Studies concerning this field used for example N, P or Ti as doping elements to obtain the desired results [47-49]. Optical properties were related with high transparency of undoped DLC under infrared and ultraviolet radiation. With doping, change of refractive index of the coating could be achieved in a precise way [50]. This means that such films could be used for manufacturing of protective optical coatings against infrared radiation.

In the further discussion, only selected elements with possible beneficial effect on DLC coatings used in biomedical applications will be described more extensively. The main focus is placed on the tribological properties as well as hardness and surface morphology of the coatings.

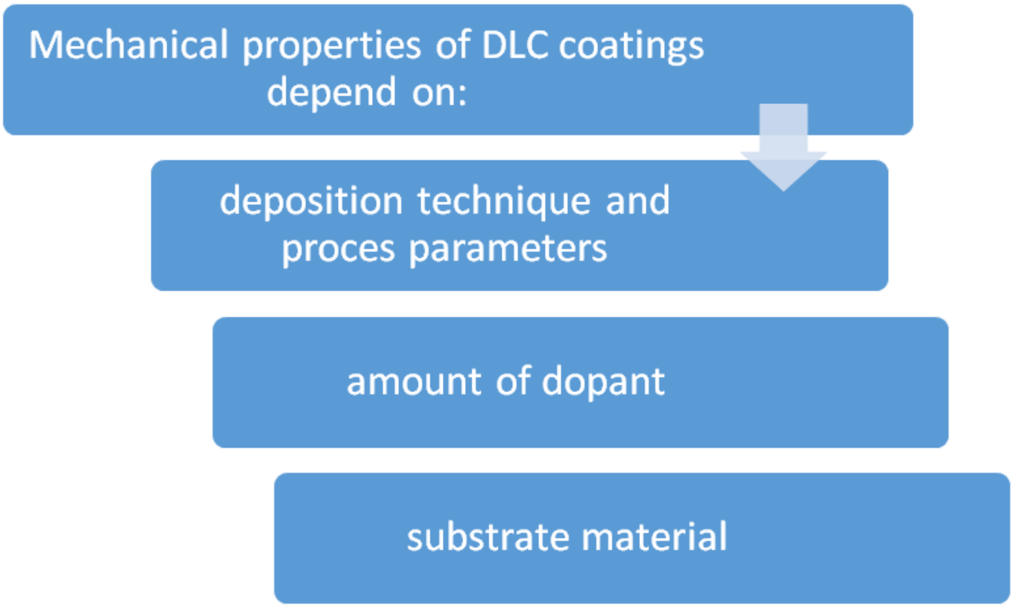

Fig. 2. Major factors affecting mechanical properties of DLC coatings
Source: Author's

Silver

Ag is a material, known for ages to possess very important biological feature - helping to fight against microbial infections. Because of this, its use as a dopant element for DLC coatings is obvious when biomedical applications are concerned. A wide number of PVD and CVD methods were used to incorporate this dopant into the DLC film, and these are: various types of sputtering techniques, plasma source ion implantation, radio frequency plasma enhanced vapour deposition, etc. [51-54]. Magnetron sputtering methods involved the use of pure Ag target [55,56] or metal pellets/bars [57] placed on the target serving as a carbon source. In some studies, Ag nanoparticles were also used. As far as the substrate material is concerned, many solutions were introduced, from glass or silicon wafers [55,56] to metallic materials [52,53]. Also, the use of interlayers like pure Si or Ti/TiN/TiCN has been evaluated [51]. Very high variations occurred also in the amount of doped Ag which typically can reach about 30%. However, Takeno et al. [54] obtained DLC composites with Ag content reaching as high as 84%.

In the case of coating synthesis by means of magnetron sputtering in the presence of argon and gaseous carbon source (methane [58], or acethylene [54]), the unfavourable adsorption of hydrocarbon onto the target surface and as a result, decrease of sputtering yields, was observed. On the other hand, by means of such phenomena, it was possible to alter the composition of the formed coating only by controlling the ratio of target poisoning/volume of the source gases. For pure magnetron sputtering, Ag concentration could be increased by application of high power to the target [56].

As far as mechanical properties are concerned, in general the presence of Ag decreased the hardness of DLC coatings. This effect was concomitant with the reduction of internal stress of the layer [57]. Wu et al. [57] and Manninen et al. [58] noticed, that in case of low amount of dopant (below 3%), the depletion in hardness can be negligible in comparison to undoped DLC. For over 10% of Ag, the drop in hardness became significant and could even decrease to 60% of the original value (similar depletion was observed for the value of Young's modulus). Reduced hardness could be explained by the fact that Ag did not build in amorphous matrix, but formed independent units of soft crystalline structure. What is more, it increased the amount of sp2 bonds [51], which do not provide the high hardness values.

Ag in DLC films is claimed to appear commonly in form of aggregates or clusters. The images of an Ag-DLC surface showed no changes in surface structure for very low amounts of Ag, however a granular character or even separated islands of dopant material were observed when Ag content exceeded 3.5% [55]. Investigation of Ag clusters with X-ray diffractometry (XRD) by Meškinis et al. [51], revealed that Ag-DLC with low dopant content (1.3%) predominantly contained crystalline Ag oxide rather than the noble metal itself. Only in films with high concentration of Ag, crystallites of various orientations were discovered. Scanning electron microscopy (SEM) and atomic force microscopy (AFM) examinations showed that the roughness and size of agglomerates increase with higher amounts of this dopant [54, 56]. One of the observed phenomena was also surface segregation of Ag with time [57]. It could lead to transformation of Ag-clusters into Ag-aggregates, and as a result influence the tribological properties of the coating.

In many cases, the dopant of soft material like Ag acted as a solid lubricant and lowered coefficient of friction [59,60]. Although Ag was usually not mentioned as a dopant leading to improved tribological properties, Yu et al. [61] claimed that Ag addition by multi-ion beam assisted deposition led to a reduction of the coefficient of friction (CoF) of the coating. These data are contradictory to studies of Manninen et al. [57], who synthetized Ag-DLC by unbalanced magnetron sputtering and obtained worse tribological properties than for undoped DLC. These two studies are examples of how various properties of undoped DLC used as a reference can influence the interpretation of the conclusive results. DLC coatings prepared by magnetron sputtering exhibited CoF on the level of 0.06-0.1 [57], while those synthetized by multi-ion beam assisted deposition had a CoF equal to 0.2 [61]. Nevertheless, in both studies (conducted under dry conditions with ball-on-disc technique), values of coefficient of friction were in the similar range, from about 0.1 to 0.2. Tendency of CoF change with increase of dopant concentration is also interesting. Manninen et al. [57] obtained an almost linear increase of coefficient of friction with an increased amount of Ag, but Yu et al. [61] showed that the lowest value could be related with an intermediate concentration between 6 and 12%. Very low CoF of Ag-DLC was obtained by Wu et al. [58]. The experiments were conducted in vacuum (10^{-3} Pa) and resulted in CoF reaching values of only 0.005. The wear resistance was depleted by the presence of Ag as a dopant. It is interesting taht in the mentioned studies, with higher amount of Ag and under lower contact pressure (690 MPa) wear rate of the coating increased only slightly , but under increased contact pressure (1180 MPa) it highly increased. Tribological tests conducted with Ag-DLC showed a formation of Ag layer on the counterpart [57]. This phenomenon was claimed to affect the tribological behaviour in different ways. On one hand, interactions of a transfer layer with aggregates of Ag in the wear track might result in increased coefficient of friction. On the other hand, graphitization of carbon could take place, leading to better lubrication properties of the coating and thus reduced coefficient of friction.

No clear dependence between Ag concentration and coating adhesion was reported. Some data state that the improved value of critical load could be obtained for all Ag concentrations within the range of about 1% to 13% [57]. Other studies showed a significant decrease of this parameter for higher amounts of Ag [52].

As the wettability is concerned, the doping with Ag led to increase of contact angle in the case of polar solvents, showing a hydrophobic character of the coating. At the same time, the drop of surface energy was observed [54,56]. However, it seems that such effect was not only the result of the dopant element itself, but also of the increased surface roughness.

Copper

Although Cu as a dopant possesses similar features as Ag, its use as additive for DLC is much less popular, even in the field of biomedical applications. Therefore, also the mechanical and physicochemical characteristics of Cu-DLC coatings are described less precisely. Introduction of Cu was performed by means of reactive magnetron sputtering, PECVD, cathodic arc deposition or by hybrid methods [62-66]. Hussain et al. [67] reported even introduction of both Cu and Ag into DLC by electrochemical technique involving use of various amounts of salts containing these elements. In the case of processes involving sputtering, the rate of deposition of Cu-DLC films was increased by increasing the plasma power, which is a typical effect for such techniques. Silicon wafers were commonly used as a substrate material, nevertheless studies concerning steel were also conducted, though in lower number.

Similarity with Ag-DLC was observed in the morphology of the coatings with Cu dopant. According to Tsai et al. [63], Cu-DLC exhibited spherical clusters of nanocrystalline particles which increased surface roughness. On the contrary, Chaus et al. [65] claimed that these coatings had a smooth surface with a roughness of 2–4 nm, having only some nanoinclusions of oxidized Cu. However, XRD analysis of Cu-DLC did not reveal the presence of high amounts of CuO [62].

The deterioration of mechanical properties of Cu-DLC was observed in comparison to undoped DLC. Commonly, hardness and Young's Modulus of Cu-doped amorphous carbon coatings were depleted with increased concentration of the doping element. Only the single study of Tsai et al. [63] claimed the increase of these parameters as a result of Hall-Petch hardening. What is more, introduction of Cu promoted sp2 bonding [64]. By means of reciprocating sliding tests, a four-times increase of Cu-DLC coefficient of friction (up to 0.23) was observed in comparison to undoped DLC (0.06-0.07) [65]. In these studies, the sliding wear also increased.

Among the improved parameters of Cu doped DLC, also a temperature dependent electrical conductivity, which can even reach a three orders higher conductivity than undoped DLC [62]. Reduced value of residual stress of the coating was observed in Cu-DLC by Pardo et al. [65] and Chan et al. [66]. Similarly as in the case of Ag-DLC, the water contact angle of the Cu containing coatings has increased compared to undoped DLC [63].

Silicon

Si-DLC is a material very important from the tribological point of view. Due to the very low friction coefficients exhibited by this material in humid atmospheres as well as at high temperatures, it was vastly investigated all over the world [41]. In CVD methods, Si-DLC was synthetized with the use of organic precursors like hexamethyldisiloxane [68] (in this case, SiO-DLC was formed), tetramethylsilane [69] and toluene [70]. It could also be obtained by sputtering of a Si target [71]. The wide range of studies were also conducted with numerous other substrate materials.

Although plenty of studies in the field of Si-DLC were conducted, many questions concerning the most basic mechanical properties still exist. Hardness and Young's Modulus of Si-DLC seem to be highly dependent on the concentration of Si in the coating. The complex studies conducted by Wang et al. [72] on films with Si content up to 14.8% showed almost no deterioration of the mentioned parameters for low Si contents (up to about 8.4%), but showed improvement for higher Si concentrations. The film containing maximum amount of dopant had a hardness above 22 GPa. In studies of Bendavid et al. [69] and Zhao et al. [73], a deterioration of hardness with an increase of Si content in the films was also observed – in both cases, decrease of coating hardness and Young modulus was observed for Si concentration not exceeding 5%. Although in the mentioned studies, the hardness of undoped DLC were about 14 and 25 GPa, respectively, , hardness values stabilised on the level of 11-12 GPa with the increase of the amount of dopant. In all three mentioned cases, PACVD method was used to synthetize the coatings. In another study, Fujimoto et al. [74] related hardness with voltage of pulse-plasma chemical vapour. In this case, -5kV of pulse voltage led to increase of coating hardness (Si content was above 5% but lower than 25%), while -2kV pulse voltage decreased the hardness (Si content was about 20%). Also in other published works, hardness was not correlated directly with the dopant concentration, but other process parameters, for example temperature of gases in the chamber [75].

The concentration of Si highly influences the already mentioned tribological parameters of Si-DLC coatings. Wang et al. [72] presented results in which low dopant content resulted in an unstable value of coefficient of friction, that could be even higher than for undoped DLC. For high dopant contents (above 11%), a low coefficient of friction (below 0.1) was obtained. Such results correlate with the data presented by Hofmann et al. [76]. In this study, CoF of Si-DLC was on the level of 0.15 for Si concentrations below 10%, while it decreased to 0.1 when dopant content was in the range of 10-25%. Also Ikeyama et al. [70] obtained the highest coefficient of friction of 0.25 for the lowest concentration of the dopant (below 1%). With an increase of Si content, CoF decreased, however this study was conducted only for Si concentrations below 10% (minimum CoF was 0.12). Low friction was claimed to be a result of the hydrated silica debris present in the track [77]. According to Kim et al. [79], only for high Si concentrations, enough SiO was present on the surface to significantly reduce the coefficient of friction. On the other hand, Gilmore et al. [78], studying the influence of moisture content on tribological properties, showed that even small amounts of Si in the coating, like 1.6 to 5.7%, could lead to a reduced coefficient of friction on the level of 0.07-0.08. Such data were obtained only for humidities between 5% and 65%, while for 85%, the CoF values were slightly higher, in the range of 0.08-1.00. In fact, for low humidity (5%), Si content of 22.1 and 35.5% led to higher CoF, between 0.55 and 0.60. Nevertheless, in 65% and 85% humidity, its value decreased to the level of 0.60.

The wear rate (described as wear surface volume divided by the load and total distance travelled by the counterface steel ball), decreased with the increase of Si concentration in the DLC coating. However, only for high amounts of Si, wear volume was lower than for undoped DLC [72]. On the other hand, in another study

[70], depth of the sliding trace decreased with the increase of Si even for low dopant concentrations. Results presented by Hofmann et al. [76] and Kim et al. (1999) [77], showed a continuous increase of the wear rate with higher amounts of Si. The influence of corrosive environment resembling body fluids on the wear resistance and friction coefficient was also examined by Kim et al. (2008) [79], however, only for low Si contents. The presence of 0.89% of NaCl during tribological tests increased the coefficient of friction in all cases. In wear-corrosive examination, devastation of the material occurred through blistering, which led to a much higher material breakdown than in a standard wear test. Corrosion rate was evaluated in corrosive and wear-corrosive environments. It was shown that abrasion related to the presence of NaCl solution led to a formation of a galvanic cell between the wear tack and the unworn surface, which resulted in massive increase of the corrosion rate.

As far as the morphology and the topography of Si-DLC are concerned, the resulting surfaces possessed a granular structure, and the roughness increased with the addition of the dopant [72]. As stated by Jones et al. [80], Si-DLC coating could to some extent even cover the inside of pits on the substrate material. It also significantly minimized the penetration of NaOH regardless of the Si content. Connected with this fact is also a good resistivity of the coating in 0.05M NaCl solution confirmed by the potentiodynamic polarization experiments [81]. The electrochemical test also showed that the coatings with higher Si content absorbed less water and ions from the corrosive environment than the coatings with lower Si content [73,79].

DLC with incorporated Si expressed lower compressive stress than an undoped DLC. In contrast to Ag-DLC and Cu-DLC, the addition of Si stabilised the sp3 fraction [81].

Fluorine

Similar to other already mentioned dopants, F was also incorporated into DLC coatings by means of various methods like cathodic vacuum arc evaporation [82], reactive magnetron sputtering [83], PECVD [84] etc. It was introduced to the process chamber in form of gaseous precursors.

Freire et al. [85] conducted studies on F-DLC films synthetized by PECVD, in which dopant concentration did not exceed 19%. Deposited coatings expressed hardness in the range of 5-6 GPa. Similar results were obtained by Bendavid et al. [86], but for a maximum 40% concentration of the dopant. In this study, for 20% of F, coating hardness was on the level of 8 GPa. In both cases, hardness of undoped DLC was similar (15-16 GPa). To increase the hardness of F doped DLC, co-doping with boron can be conducted. BF-DLC films were synthetized with plasma immersion ion method by He et al. [78]. These coatings were prepared on four substrates: silicon, glass, polymethyl methacrylate and polycarbonate. Films on the first two materials a had hardness of over 17 GPa for F content of up to 10%. For higher F concentrations, it was at least 15 GPa (in both cases concentration of boron was fixed to about 4%). Unfortunately, no data concerning the tribological properties of BF-DLC were provided.

Research conducted by Donnet et al. [88] showed a strict correlation between the amount of F and the mechanical properties of F-DLC coatings, especially their wear resistance. When the ratio of F/(F + C) was lower than 0.2, the wear resistance was similar to undoped DLC and could be tailored by adjusting the deposition conditions (high deposition bias, low gas pressure etc.) [85].

In work of Sung et al. [40], the name "dialon" appeared for fluorinated DLC. It stands for diamond-teflon material fabricated by RF PECVD method, with a friction coefficient of less than 0.001. On the other hand, Wang et al. [89] examined DLC terminated with F. Quantitative calculations of such coating models had a CoF between 0.08 and 0.09. Experiments performed on the material sample showed that F content in the range of 1-20% led to a gradual reduction of coefficient of friction to the level of 0.12 [85].

As far as the roughness of the F doped DLC coatings is concerned, addition of this dopant led to an increase of this parameter [83]. In the literature, such tendency was correlated with etching of the surface during PECVD process [90,91].

F-DLC is a hydrophobic coating, where water contact angle can reach over 90° [83]. Saitoa et al. [84] examined values of contact angle with human blood and obtained an almost 4-times increase of this parameter in comparison to the substrate material, which was silicon. With an increasing amount of the dopant, a decrease of the total surface energy and its dispersive component was observed. Value of polar component was growing due to the presence of more unsaturated bonds on the surface (coating graphitisation). Bonds from the F-DLC surface (lower amount of –C–CF, and higher amount of –CF and $–CF_2$) were identified as a reason for the drop of dispersive component of surface energy [74, 81]. Raman spectroscopy in studies of Marciano et al. [92] and Bendavid [86] et al. showed an increase of ID/IG ratio of coatings with higher amounts of F. The incorporation of this dopant also reduced the compressive stress of DLC layers.

Addition of F also had a positive influence on DLC electrochemical corrosion resistance, which was evaluated by potentiodynamic polarization test by Marciano et al. [92]. Less than 2% of the dopant reduced corrosion current density by more than one order of magnitude in comparison to the undoped DLC films.

Titanium

Ti is the most commonly used dopant of the seven elements selected for this review. This is why in the literature, various techniques were used to incorporate it into the DLC matrix [92-97]. Moreover, precise evaluation of synthesis parameters and of mechanical properties of these coatings have been done in many cases. The process of coating synthesis could also involve fabrication of single or multiple interlayers concerning pure metal, its carbide or other compounds [98]. Ti-DLC was synthetized on various substrates, both metallic and non-metallic ones. To obtain improved properties also multi-dopant systems were used, for example by using Ti and Cr [99].

X-ray photoelectron spectroscopy (XPS) proved that Ti was incorporated into the amorphous carbon structure in form of titanium carbide (TiC) nanoparticles for high dopant content. The exact percentage of Ti that could dissolve in DLC varies in the literature from 0.9 and 2.5 up to 16% [100,101]. Dai et al. [102] claimed that Ti reduced compressive stress when it was present in low amounts, but increased it when its content in the coating exceeded 8%. Such phenomenon was correlated to the already mentioned solubility of Ti in DLC matrix. When this element was uniformly distributed in a matrix, it acted as a pivotal site for occurring distortions of atomic bonds. High Ti content led to a formation of Ti-C bonds which were longer than conventional C-C ones, so that the compressive stress of the coating was increased.

There are no consistent data concerning the influence of low amounts of Ti on sp2 and sp3 fraction. By means of Raman spectroscopy, Qiang et al. [103] evaluated that doping of DLC with Ti decreased the sp3/sp2 ratio for low concentrations of the dopant, but Dai et al. [102] provided opposite results: for higher addition of Ti, graphitization of the coating occurred, and this phenomenon was related with the increase of sp2 hybridization of carbon by Qiang et al. [104].

Looking at the change of sp2/sp3 ratio due to doping with Ti, it could be assumed that generally hardness would drop because of the graphitization process [94,97]. Nevertheless, part of the literature, for example data presented by Ma et al. [93], showed just the opposite. The reason of such state was claimed to be the increasing presence of hard TiC nanoparticles, which not only alleviated the higher amount of sp2 fraction, but also further increased the coating hardness. As far as the process parameters are concerned, hardness of DLC coating increased after doping with Ti and with increasing substrate bias [105]. When at the same time target-substrate distance was considered, for high voltage bias hardness was increasing with a higher separation of the substrate and the target. For low substrate voltage bias, hardness decreased for processes conducted with higher distances. In general, experiments involving high power plasma magnetron sputtering revealed that substrate-target distance rather than substrate bias has a predominant effect on Ti content and hardness. Taking the above into consideration, hardness of Ti-DLC was the result of not only Ti concentration but also of the parameters of the synthesis process.

The morphology of Ti-DLC surface depends on TiC formation process. The formation of micro and sub-micro sized nanoparticles led to a roughening of the surface [94]. Moreover, in the case of low Ti content, the smoothness of undoped DLC was almost maintained [103].

By the experiments involving ball on disc test, higher adhesion of the coating to the metal substrate was claimed [102]. This was also confirmed by means of a scratch test (even a 3.5-time improvement of the adhesion strength) [94]. Moreover, Ti-DLC was characterised by a reduced coefficient of friction (to 0.2-0.1 [97] or even 0.04 [103]). As Gilmore et al. [78] showed in their study, the difference between CoF obtained for humidity of various values can be higher than 0.05. The lowest coefficient of friction (below 0.05) was obtained for the lowest humidity (5%). When wear resistance of the coating was concerned, the best solution was to limit the amount of doping [94]. The presence of TiC nano and microparticles led to abrasion of the material. Ball-on-disc testing with steel balls as counterparts showed high wear rates and unusual W-shape wear tracks [102]. Such shape was present due to the occurrence of high amount of wear debris originating from the counterpart.

The addition of Ti also influenced the hydrophobicity of the coating surface. Increase of water contact angle (to 130°) was observed in contrast to undoped DLC (70°) [93]. Ti was also responsible for the decrease of the resistivity of the doped coating [106].

Calcium

There are not many studies concerning the use of Ca as a dopant material for DLC coatings. In the literature, mostly incorporation of calcium oxide rather than undoped Ca was considered. Moreover, the published studies were focused on biological evaluation and not mechanical properties of the obtained coatings. Only two different methods were used for the synthesis of these layers.

The first attempts to develop DLC with Ca or its derivatives were conducted using a direct current discharge by Dorner-Reisel et al. [107,108]. Gases used during the coating fabrication were methane and CaO-H_2O vapours. In the case of this method, decomposition of both hydrocarbon and Ca precursors took place in the synthesis chamber. As a result, Ca was introduced to the Ca-O-DLC in form of carbonate, which was confirmed by the data obtained with XPS and IR-spectroscopy. The rate of deposition reached about 16 nm per minute which was lower than in the case of undoped DLC (about 19 nm per minute). Studies involving this method provide a good description of both basic mechanical and biological properties of these coatings. What is more, the synthesis was conducted on a metal substrate – Ti6Al4V, which shows a possibility of future implementation of such technique for implants. Authors claimed that the presence of Ca in the coating led to a drop of hardness, Young's Modulus and relative elastic recovery of the coating. On the other hand, with the increase of CaO-H_2O partial pressure, the difference between mechanical properties of doped and undoped DLC decreased. With the addition of Ca-O to the DLC matrix, the adhesion of the coating was improved. The major drawback of the presented studies is that Ca content was estimated only by considering the partial pressure of CaO-H_2O and no quantitative estimation was made.

The second technique of incorporation of Ca to DLC coating was based on plasma immersion ion implantation and deposition (PIII and D), with the use of a pure Ca powder [109]. The mixed gas plasma was obtained by evaporation of Ca with the addition of acetylene and argon. Unfortunately, the physicochemical examination of coatings synthetized this way was narrowed only to evaluations of contact angle, interfacial energy between samples and water, and elemental depth profiles obtained with XPS. XPS showed a stable Ca concentration (on the level of about 10%) within the depth of 60 nm, while a rather sharp interface between carbon (from the coating) and silicon (from the substrate material) was observed at around 25 nm.

Phosphorus

Similarly as in the case of Ca, not many studies were devoted to the investigation of phosphorous doped DLC. These investigations covered synthesis of films with the use of phosphane (-PH_3) gas [110] or evaporated red P powder [109], while the common techniques are PIII and D and filtered cathodic arc method. One of the interesting experiments involved formation of a target for the pulsed laser deposition in form of pellets made of burned camphor mixed with various amount of red P [47]. Since doping of DLC with P was mostly targeted on obtaining better electronic properties of the coating, the majority of published data did not thoroughly describe the mechanical properties, usually only the increase of roughness in comparison to the undoped DLC was denoted [112]. Some additional studies involving multi-dopant DLC coatings with both Ca and P were published, yet they focused on biocompatibility and hemocompatibility [109].

The studies were mostly concerned with the low amount of doped P – on the level of 0.2-3%, but in some cases the atomic concentration on the surface reached almost 20%. The addition of about 1 % of P was claimed not to alter the tetrahedral network of bonds present in the DLC coating, however only 3% of this dopant increased the amount of sp2 bonds [113]. P-DLC exhibited several orders of magnitude lower resistivity than undoped

DLC. Data concerning hardness showed better properties of P doped DLC, but not in a linear dependence with the dopant concentration. Maximum value of hardness (9.34 GPa) at 50 gm load was obtained for 1% P-DLC. All studies showed a very good wettability of P-DLC coatings with polar solvents (in some studies, the contact angle value was only 17°) [112, 113].

One of the characteristic features of P doped DLC is its microstructure resembling numerous dots evenly distributed on the surface, as presented by Kwok et al. [113]. Their parameters could be averaged to about 8-18 µm of diameter and 20-50 nm of height. The conducted chemical composition evaluation by means of energy-dispersive X-ray spectroscopy (EDX) allowed to determine that only the spots contained P.

Little data concerning the rate of deposition of P-DLC has been reported. The use of phosphine could alter it from about 15 up to about 35 nm per minute. What is interesting, the highest improvement of the growth rate was observed for the low flow of PH_3 (maximum improvement of about 25% occurred for just 1.25% of P precursor concentration) [110].

Discussion

Although there are many studies concerning doping of DLC coatings with Ag, Si, F, Cu, Ti, Ca and P, it was complicated to compare the obtained results. The reason for this is related with a variety of techniques used for fabrication of coatings by research groups from all around the world, which result in different properties of even undoped DLC. What is more, numerous studies were conducted on silicon wafers and not on metallic substrates. Data obtained in this way may be promising, but for the sake of biomedical applications, the obvious requirement is the use of materials commonly available on the market of implants and/or medical equipment (titanium alloys, 316L steel, etc.). Only such studies can be fully informative and enable estimation of implementation possibility of the developed technology to the medical use.

Table 1. Comparison of the influence of the dopant concentration on the hardness of doped DLC coatings

Doping element	Dopant effect on hardness in comparison to undoped DLC	Hardness range of doped DLC
Ag	reduction of hardness	from ~7.5 GPa (~3.5at.%) to ~4.5 GPa (~11.0 at.%) [58] from ~13.0 GPa (~2at.%) to ~9.5 GPa (~13.0 at.%) [57] from ~13.0 GPa (~4.5at.%) to ~11.0 GPa (~15.0 at.%) [52]
Cu	reduction of hardness	from ~24.0 GPa (~5.0 at .%) to ~13.0 GPa (~30.0 at.%) [65] from ~16.0 GPa (~11.0 at.%) to ~15.0 GPa (~23,0 at.%) [66]
	no data	from ~2.75 GPa (no exact data) to ~3.25 GPa(no exact data) [63]
Si	reduction of hardness	from ~12.5 GPa (~4 at.%) to ~12 GPa (~13.0 at.%) [69] from ~20.0 GPa (~2.5 at.%) to ~13.7 GPa (~22,0 at.%) [73]
	increase of hardness	from ~12.0 GPa (~7.0 at.%) to ~22.0 GPa (~23,0 at.%) [72] from ~16.0 GPa (~7.5 at.%) to ~18.7 GPa (~22,5 at.%) [74] from ~24.0 GPa (~5.0 at.%) to ~27.0 GPa (~25,0 at.%) [76]
F	reduction of hardness	from ~16.0 GPa (~6.5 at.%) to ~6.0 GPa (~39.0 at.%) [86] from ~18.5 GPa (~12.5 at.%) to ~16.0 GPa (~37.5 at.%) [91]
	increase of hardness	from ~5.5 GPa (~3.0 at.%) to ~7.0 GPa (~19.0 at.%) [85]
Ti	reduction of hardness	from ~20.0 GPa (~1.0 at.%) to ~12.5 GPa (~4.0 at.%) [96] from ~27.5 GPa (~2.0 at.%) to ~17.5 GPa (~20.0 at.%) [97] from ~13.0 GPa (~0.5 at.%) to ~10.0 GPa ~8.0 at.%) [94]
	increase of hardness	from ~15.0 GPa (~5.0 at.%) to ~22.0 GPa (~24.0 at.%) [94] from ~10.0 GPa (~5.0 at.%) to ~20.0 GPa (~40.0 at.%) [100] from ~20.0 GPa (~4.0 at.%) to ~27.5 GPa (~24.0 at.%) [102] from ~30.0 GPa (~1.0 at.%) to ~32.0 GPa (~6.0 at.%) [106]
Ca	reduction of hardness	from ~18.0 GPa (no exact data) to ~9.5 GPa (no exact data) [107]
P	no effect	about 9 GPa (from 0.5at.% to 2.0at.%) [112]

Source: Author's

The addition of dopants described in the following article affected (i) the mechanical properties of DLC coatings: hardness (see table 1.), adhesion etc.; (ii) tribology (see table 2.) and (iii) also morphology or surface energy of the deposited coatings. Comparison of the influence of dopant concentration on the hardness of doped DLC coatings presented in table 1. shows that no clear trends how Si, Ti and F affect even a single, most basic property of the fabricated coating such as hardness can be recognised, because both reduction and improvement of this parameter was reported in comparison to undoped films. The described values of hardness of doped DLC coatings were in the range from about 2.5 GPa to over 30 GPa. Only in the case of Si-DLC and Ti-DLC the hardness of films was higher than 10 GPa for all the described concentrations of the dopant. From this point of view, doping of DLC with these elements has the highest potential in biomedical applications requiring superior mechanical endurance (e.g. for orthopedic implants). With these elements also a reduction of coefficient of friction was observed, which may be advantageous in friction joints such as hip or knee prosthesis.

In predominant number of the presented studies, the examination of mechanical and physicochemical properties of doped DLC coatings was performed for samples with concentration of dopant element higher than 4 at.%. Since biological properties can be highly affected even with very low concentrations of the doping element [114], mechanical properties of such films should also be examined.

Properties of P-DLC and Ca-DLC are the least described. Tribology of these coatings was so far under minor investigation of researchers (see TABLE 2). What is more, the descriptions of other mechanical and physicochemical properties of P-DLC and Ca-DLC are also rather limited - authors focused primarily on the evaluation of their biological aspects. Lack of vast examination considering major functional properties of P and Ca doped DLC films prevented from objective evaluation of their biomedical potential.

Table 2. Comparison of tribological properties of doped DLC coatings with undoped films

Doping element	**Increased CoF**	**Decreased CoF**
Ag	YES*	YES*
Cu	YES	
Si		For high concentration
F	YES*	YES*
Ti	For high concentration	For low concentration
Ca	No data	No data
P	No data	No data

Source: Author's. **** Depends on the properties of undoped DLC coating***

Conclusions

Undoubtedly there are numerous studies considering the properties of doped DLC films which are reported in the available literature, and the stage has been reached at which tailoring of the properties of fabricated films should be considered for biomedical applications. In the present study, DLC coatings doped with Ag, Si, F, Cu, Ti, Ca and P are investigated in terms of mechanical and physicochemical properties regardless of their deposition technique or substrate material, which provides a wide range of functional properties that are achievable. Nevertheless, detailed studies considering the fabrication of coatings with various dopants and different deposition techniques are necessary to enable a direct comparison of the influence of each element. More experiments should be performed with the use of substrate materials common for biomedical applications: metallic polymeric and ceramic. This way, the studies could be easier correlated with the ways of their implementation in the industry.

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THE INFLUENCE OF OUTLET SYSTEM GEOMETRY ON TESLA TURBINE WORKING PARAMETERS

Abstract
The paper presents an analysis of the influence of Tesla turbine outlet system geometry on parameter distribution and power. Simulations were carried out with the aid of Ansys products: DesignModeler, Meshing and CFX 17.0. The model geometry was based on the dimensions of existing turbine. Three different types of outlet system were investigated. A mesh independence study was carried out in order to obtain results which were unaffected by discretization method. Computations were performed using experimental data. The flow phenomena occurring inside the turbine are described in addition to the differences caused by outlet system geometry. Numerical results were confronted with experimental analysis.

Key words
Tesla turbine, CFD, bladeless turbine

Introduction

Tesla turbine, also known as the bladeless turbine, was manufactured for the first time in 1906 by Nikola Tesla and was patented in 1913 [1]. Due to lack of funds and materials able to withstand tensile stresses, Tesla was forced to abandon investigation into this turbine type. Developments in materials technology and unique advantages have resulted in a renewed interest in bladeless turbine. Many experimental analysis have been performed, which have contributed to broaden the knowledge of flow in the Tesla turbine. Lemma et al. [2] carried out experimental analysis of the Tesla turbine with 50 mm diameter rotor with the air as working medium. The highest obtained efficiency was 23.1%. Hoya and Guha [3] constructed turbine with rotor diameter of 92 mm. They obtained the highest efficiency of 25% and power of 140 W.

Tesla turbine has many advantages [4], including among others: a simple geometry which significantly decreases manufacturing cost, resistance to erosion and high flexibility in choice of working medium. These advantages allow for the opportunity to use bladeless turbines in ORC installations or installations powered by renewable energy sources. Lampart and Jędrzejewski [5] performed numerical analysis of Tesla turbine using a low boiling medium. The results proved, that isentropic efficiency could reach 50%. Ho-Yan [6] performed analytical investigation of Tesla turbine for pico hydro applications. Carey [7] analysed use of Tesla turbine for small scale Rankine system. He derived dimensionless parameters and determined their values, which could provide turbine isentropic efficiency within range of 80-90%. Sengupta and Guha [8] performed computational and experimental analysis concerning flow of a nanofluid in Tesla turbine. They proved that use of nanofluids can increase generated power without any major drop in efficiency.

The principle of operation of the turbine is based on the phenomena of adhesion and viscosity. The working fluid adheres to the disc's surface because the adhesive forces between fluid particles and disc particles are greater than the cohesive forces within the fluid alone. Energy transfer from the fluid to disc occurs by means of momentum diffusion: the momentum of the faster moving fluid layers decreases due to the absorption of particles from slower moving layers. The reverse process contributes to increasing momentum of slower layers.

The most important part, which distinguishes the Tesla turbine from others, is the rotor. It consist of multiple thin disc mounted on a common shaft. Between the discs, spacers are placed whose aim is to hold the discs at a constant distance from each other during exploitation. Important part of construction is also the supply system. The working medium expands in the inlet nozzle, increasing its speed at the expense of pressure drop. Depending on nozzle geometry, the fluid velocity might be equal to or even greater than the speed of sound [9]. Working medium flows tangentially to the discs' surfaces, where the expansion is continued. Due to high velocity gradients, shear stresses occur and torque is produced, which propels the rotor. Streamlines from the inlet to the outlet are spirally shaped, due to centrifugal force. The geometry of the outlet system is also very important as it influences parameter distribution in the rotor, power output and shape of outlet flow.

The most important issue with Tesla turbine is efficiency. Although rotor efficiency could be very high, as in conventional rotors [10], it is very difficult to design efficient inlet and outlet systems. Neckel and Godinho [9] investigated phenomena occurring in nozzles with the use of Schilieren technique. The most undesirable phenomena which decrease nozzle efficiency was shock wave. They tried to determine geometry, which could decrease total pressure losses and thereby improve overall Tesla turbine efficiency. Hoya and Guha [3] used loss of total pressure as an assessment of nozzle efficiency. Loss coefficient, which express energy degraded by friction, was approximately 10 times higher in nozzle of Tesla turbine than typical value of this coefficient in gas turbine nozzle. Guha and Smiley [11] designed and tested nozzle utilizing a plenum chamber inlet. Experiments showed less than 1 per cent loss in total pressure compared to losses in the range 13-34 per cent for the original nozzle and inlet. Thickness of the gap between the discs also has a great impact on turbine efficiency [12].

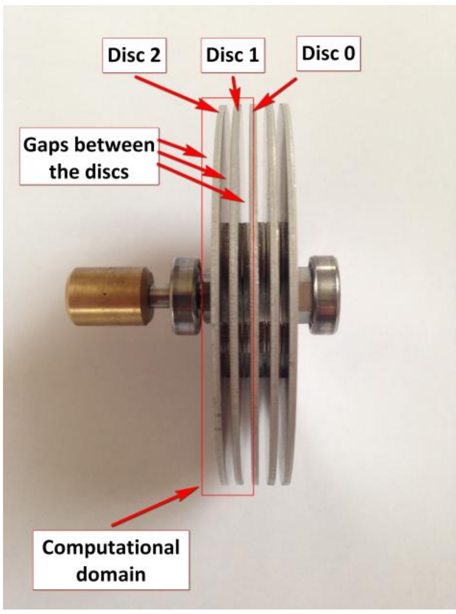
Geometry of outlet system also contributes to turbine efficiency loss [13], but there is relatively little literature devoted to that problem. Li et al. [14] conducted experimental study of the Tesla turbine propelled by incompressible fluid. They discovered that rotational speed has a significant influence on exit partial loss.

In this paper, an analysis of the influence of outlet system geometry on parameter distribution and on forming of flow phenomena was carried out. Numerical analysis was performed with the aid of Ansys products: DesignModeler for creating the geometry of the model, Meshing for discretization and CFX 17.0 for physical model and computations.

Numerical models

Geometry models were based on existing turbine dimensions. The rotor consisted of 5 flat discs of 73 mm diameter, 1,3 mm thickness and 1,5 mm spacing. The rotor of turbine with labels and front view of a single disc are presented in Fig. 1. Flow from the rotor to the outlet system was carried out through 5 holes with diameter of 7,5 mm. Numerical models included only half of the turbine, i.e. two discs and one surface of the third disc, supply and outlet systems (labelled in Fig. 1a as computational domain). Detailed models of computational domains with labels are shown in Fig.2.

a)



b)

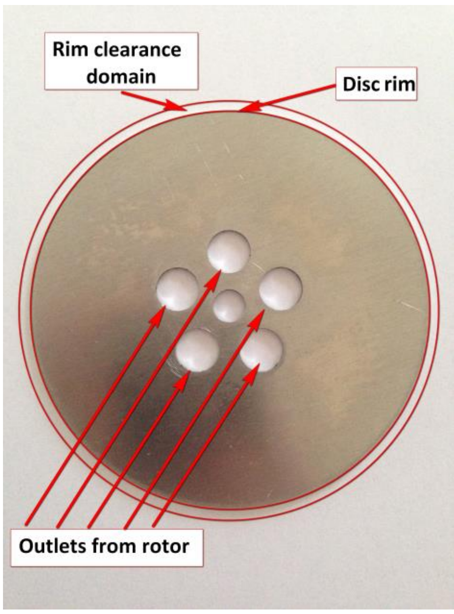


Fig. 1 a) Rotor of the Tesla turbine with labels and b) front view of single disc
Source: Author's

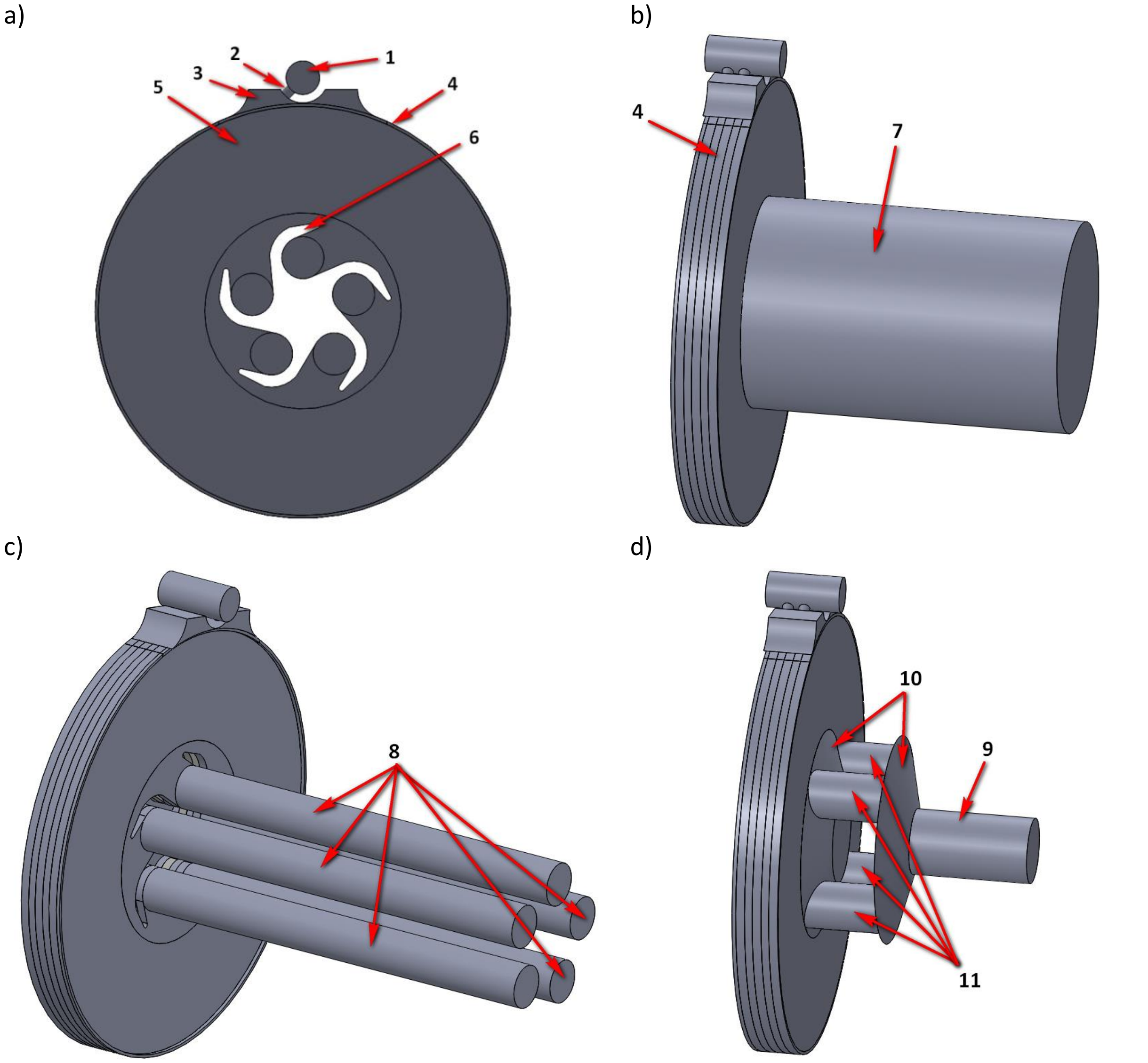


Fig. 2. Computational domains: a) front view of models with spacers, b) model I, c) model II, d) model III
Source: Author's

The supply system consisted of a supply chamber (label 1 in Fig. 1a), from which the medium was delivered between the rotor discs by means of two holes in the chamber wall (2). Domain labelled 3 represents space between inlet system and rotor. The rim clearance (4) between the discs rims and turbine casing was also modelled. The gap between the discs in which outflow from inlet ducts was carried out, is labelled as number 5. Only in case of disc 1 propulsion was carried out in both sides of the disc. In models II and III the impact of spacers (one of them is labelled 6), which are placed between the discs was taken into consideration. Spacers were responsible for holding constant distance between the discs during operation but also contributed to outflow organization due to their characteristic shape. In model I the outlet system was placed instead of shaped spacers. It consisted of one cylinder (7) with a diameter of 35 mm. In model II the spacers were taken into consideration. Outflow was carried out by means of five cylinders (8) with diameter of 7,5 mm. Model III reflected the exact outlet system geometry of existing turbine, consisting of an outflow duct (9) to ambient air and two choking chambers (10) connected to each other by 4 cylindrical linkages (11). In this model, spacers were also taken into consideration.

In order to obtain results which are unaffected by the discretization method applied to the gap between the discs and inlet system, a mesh independence study was performed. To do so, computations on five different unstructured meshes were carried out and the values of power output were compared. Power obtained from the finest mesh was considered as reference power, to which other result were compared. In Fig. 3 part of the mesh no. 3 is depicted.

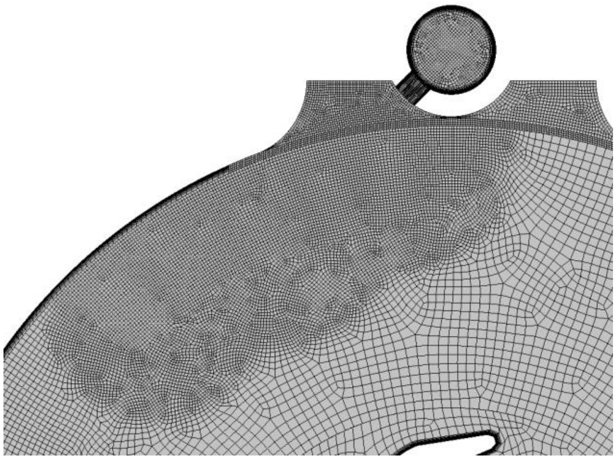


Fig. 3 Part of model discretization
Source: Author's

Meshes were finer in areas with a high velocity gradient, i.e. after inlet ducts where the jet was being formed. Furthermore, due to phenomena occurring in boundary layer, which are extremely important in shear stress generation, discretization of this area had to provide distribution of y^+ parameter below 1 throughout the whole domain between the discs. The same method of discretisation was utilised for the inlet system in order to obtain an appropriate model of flow contraction at the inlet duct.

Computations were performed in a steady state, single precision solver. Equations of mass, momentum and energy conservation were solved [15]:

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \boldsymbol{U}) = 0 \tag{1}$$

$$\frac{\partial \rho \boldsymbol{U}}{\partial t} + \nabla \cdot (\rho \boldsymbol{U} \otimes \boldsymbol{U}) = -\nabla \mathrm{p} + \nabla \tau \tag{2}$$

$$\frac{\partial \rho h_{tot}}{\partial t} - \frac{\partial p}{\partial t} + \nabla \cdot (\rho \boldsymbol{U} h_{tot}) = \nabla \cdot (\lambda \nabla \mathrm{T}) + \nabla \cdot (\mathbf{U} \cdot \tau) \tag{3}$$

The stress tensor τ is related to the strain rate by means of the following expression:

$$\tau = (\mu + \mu_t)\left(\nabla \boldsymbol{U} + (\nabla \boldsymbol{U})^T - \frac{2}{3}\delta \nabla \cdot \boldsymbol{U}\right) \tag{4}$$

Working medium was air treated as an ideal gas with constant dynamic viscosity and thermal conductivity. Parameters at the inlet were: absolute total pressure 3 bar and total temperature 303 K. Domains of gap between the discs were stationary, although walls of these domains were rotating with velocity equal to 21000 rev/min. It simulated rotational movement of disc, because walls of the disc are also walls of gap between the discs domain. In addition no slip wall boundary condition was set on these walls. In case of models II and III, spacer domains were also rotating with the same velocity as disc walls. This domains were connected with domains of gap between the discs with frozen rotor interface. In models I and III outlet systems were stationary, but in model II five cylinders were rotating with the same angular velocity as the spacers. It is caused by a fact, that these cylinders are jointed directly with spacer domain. An opening boundary condition with pressure of 1 bar and temperature of 293 K was implemented at the outlet in models I and II. In model III, an outlet boundary condition with average static pressure 1 bar was applied. All flow parameters were based on results obtained from experimental data. High resolution advection scheme and high resolution turbulence numerical scheme were utilised. Conservative auto timescale control with 0.5 timescale factor was applied. The convergence criterion for residuals was set as 10^{-3}.

It was important to obtain as accurate solution for the boundary layer as possible due to a fact that shear stresses, which determine power, are generated in that region. This condition could have been satisfied by using k-ω turbulence model. On the other hand, this turbulence model does not provide accurate results for the freestream region, which could lead to wrong conclusions regarding phenomena developing e.g. in the jet. Rotation also introduced effects on turbulence like inverse flow or inhomogeneities, which were additional difficulties in modelling. Large Eddy Simulations are confirmed to provide appropriate level of modelling for rotating flows with fully turbulent regimes [16]. However computational cost is significantly higher compared to RANS simulations. Therefore k-ω SST model was employed, which is also often and successfully used in modelling of the Tesla turbine, e.g. in [17].

Results

In the Fig. 4 dependence of the number of mesh elements on the power is depicted. It can be seen, that the mesh with 4 100 000 elements (4 263 000 nodes) provides sufficient level of accuracy. The boundary layer mesh providing distribution of y^+ below 1 consisted of 24 layers with the first element of $5 \cdot 10^{-5}$ m of height. Results of computation performed with use of this discretisation method are presented below.

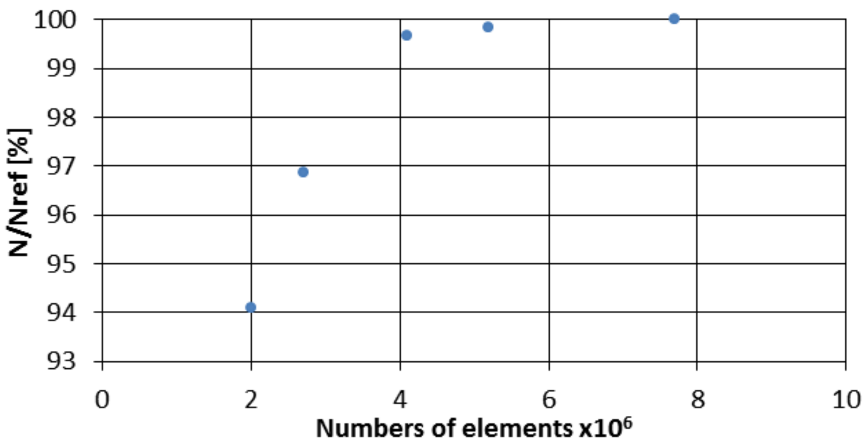


Fig.4. Dependence of the number of mesh elements on the power
Source: Author's

Power obtained from preliminary experiment and model III are compared to each other. Value computed in numerical analysis has to be multiplied by two, because only half of the turbine was modelled. Results are presented in Tab. 1.

Tab. 1 Comparison of the power obtained from the numerical analysis and the experiment

Experimental analysis (W)	Numerical analysis (W)	Relative difference (%)
41,6	54,2	23,2

Source: Author's

The relative difference is equal to 23,2 %. Taking into consideration fact, that this is only preliminary experiment, convergence of the results might be considered as satisficing. As far as numerical analysis is concerned, simulation did not take into account nonstationary effects, which possibly could change value of power. Therefore computations in unsteady state might provide better results. Additionally application of Large Eddy Simulations as turbulence model could also improve prediction of turbine performance.

In the Fig. 5 static pressure distribution in the middle of gap between the discs 0 - 1 and a comparison between models II and III are presented. It can be observed that the working medium in each model expands in inlet duct to pressure of approximately 120 kPa. This pressure is smaller than the critical pressure for the given conditions (158 kPa) so the Mach number is greater than 1. Mach number distribution is shown in Fig. 6.

The pressure at the outlet from the inlet duct is too high for the conditions in the gap between the discs; hence, overexpansion and overcompression occur. These phenomena take place alternately and slowly diminish. The working medium forms a jet which spreads from the inlet of the duct to the rims of the discs. The maximum Mach number in the jet is observed slightly after the inlet and is equal to 1,3. The jet is bent towards the disc rims due to centrifugal forces acting on the fluid particles. These forces come from the high rotational velocity. Between the jet and disc rims "swirled region" occurs, i.e. an area with a low velocity and unorganized flow. This is a disadvantageous phenomenon, as this area, located far from the axis of the turbine shaft, powered properly could significantly increase the generated torque and power of the turbine. Furthermore, the current supply system configuration causes swirls and backflows, which also decrease torque. The parameter distributions depicted in this area differ depending on the model. In model I "swirled region" has the greatest area its velocity fluctuates between 5 ms^{-1} – 70 ms^{-1}. In model II this region has the smallest area and a velocity between 50 ms^{-1} – 90 ms^{-1}. In model III the velocity is between 5 ms^{-1} – 55 ms^{-1} and the area of this region smaller than in model I and greater than in model II. Another undesirable phenomenon is leakage in the rim clearance. Medium expands beyond the limits of the rotor and thus does not contribute to generation of torque. Differences in Mach number and static pressure distribution between models II and III are shown in Fig.5d and Fig.6d. It can be observed that the biggest differences are in the jet area (up to 0,5 Mach and 7 kPa) and in the outlet system. The jet direction is also different, caused by, among others, different outlet system geometries.

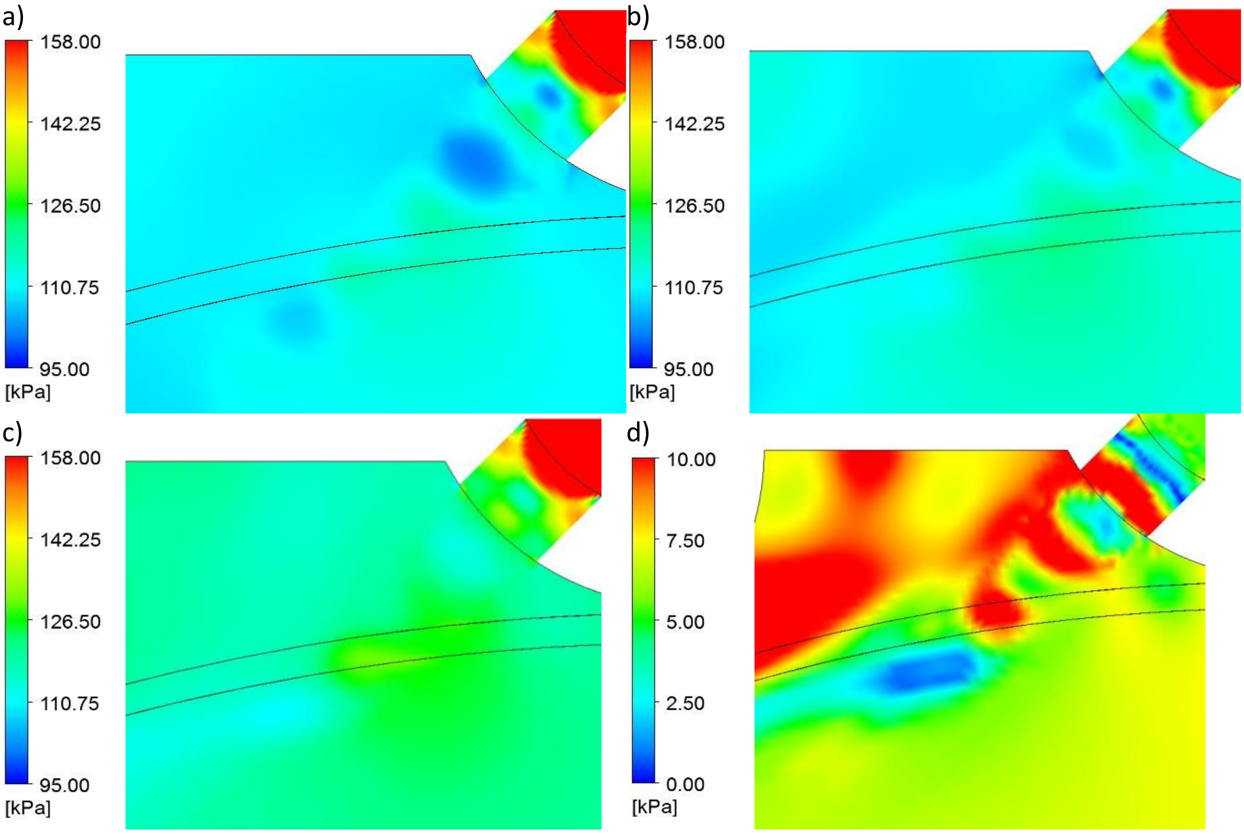


Fig. 5 Static pressure distribution a) in model I, b) in model II, c) in model III and d) difference between models II and III
Source: Author's

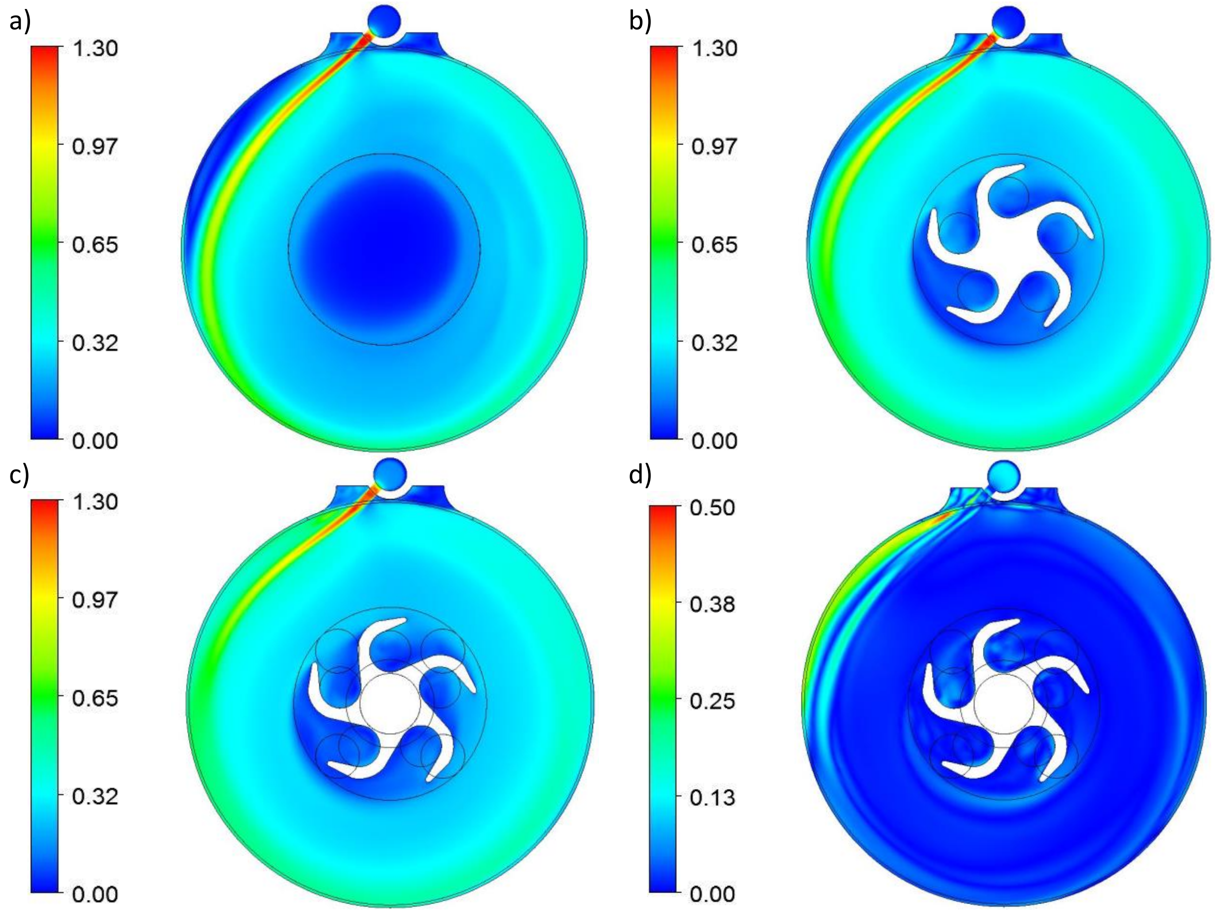
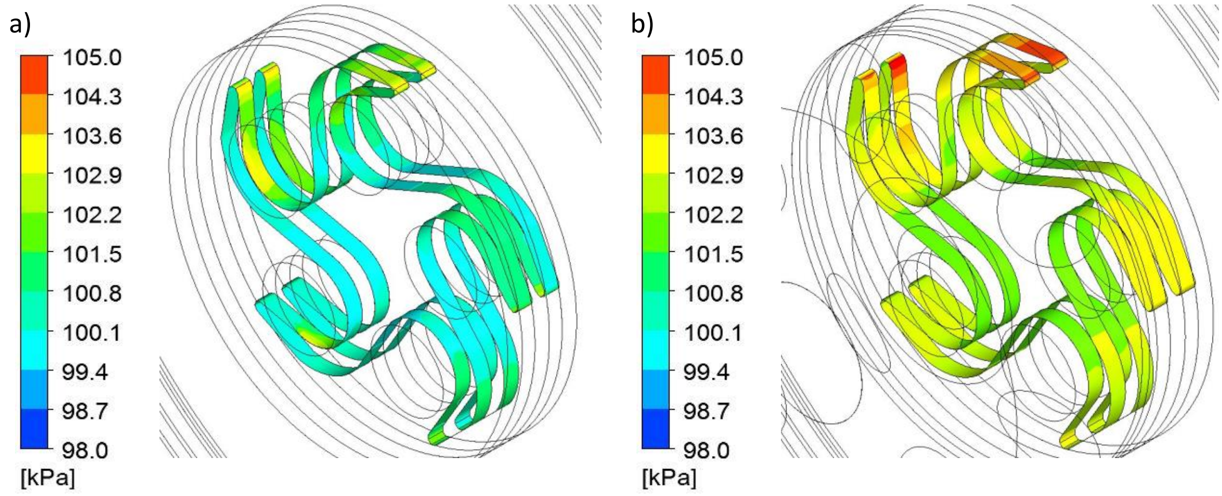


Fig. 6 Mach number distribution a) in model I, b) in model II, c) in model III and d) difference between models II and III
Source: Author's

The geometry of model III is more complicated which causes a larger pressure drop in the outlet system; hence, expansion between the discs is carried out to a greater extent than in model II. This can be observed in Fig. 7, which presents the static pressure distribution on the spacer walls.



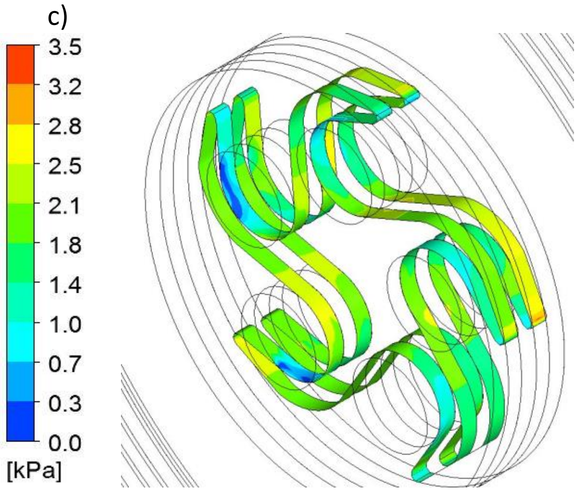
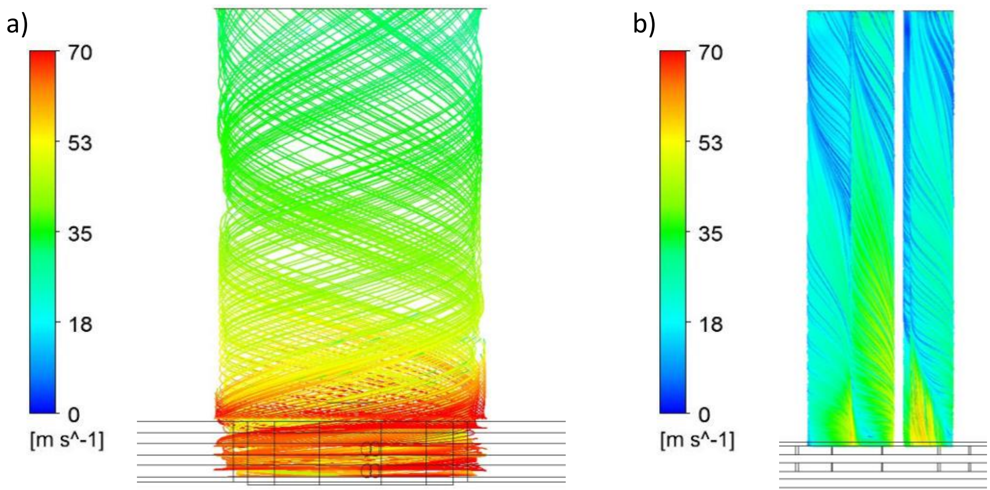


Fig. 7 Static pressure on spacers a) in model II b) in model III c) difference between models II and III
Source: Author's

The maximum value of static pressure acting on the spacers in model III is equal to 105 kPa and minimum is equal to 99 kPa. In model II, the average static pressure is lower than in model III, with a difference of up to 3,5 kPa. The pressure force acts on the walls of the spacers, so additional torque is generated in this area.

In Fig. 8 streamlines in the outlet systems are presented. In each model, the outlet jet is strongly swirled. In the middle of the swirls, negative pressure (approximately 2 kPa) occurs. This could lead to small backflows into elements of outlet system. The average outflow velocities in models I, II and III are equal to: 15,15 ms^{-1}; 25,92 ms^{-1} and 34,45 ms^{-1} respectively. This velocity depends on the diameter of the outlet duct, so in model I, where the diameter of the outlet section is largest, the velocity is relatively small. Higher velocities in the outlet section leads to greater kinematic loss. In model III presence of 2 choking chambers did not prevent flow from forming swirled structures.



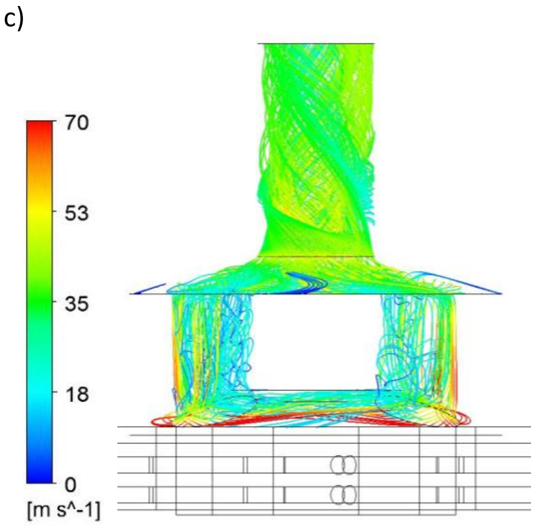


Fig. 8 Streamline in outlet system of a) model I, b) model II, c) model III
Source: Author's

For each model, the power output based on torque and angular velocity was obtained. Torque was computed from shear stress and distance from the shaft axis. Shear stress values were calculated based on velocity gradient, dynamic viscosity and eddy viscosity. Power was calculated for disc surfaces, disc rims and spacer walls. The results are presented in Tab. 2.

Tab.2 Power obtained from numerical models

Area	**Power [W]**		
	Model I	**Model II**	**Model III**
Disc 1	10,68	13,04	11,36
Disc 2	7,10	8,06	7,83
Disc 0	5,27	6,93	6,07
Rim 1	0,69	0,86	0,67
Rim 2	0,71	0,67	0,69
Rim 0	0,06	0,02	-0,04
Spacer 1	-	0,99	0,33
Spacer 2	-	1,17	0,19
Total	**24,51**	**31,74**	**27,10**

Source: Author's

The highest power was obtained from model II. The differences between the models in power generated by the discs are partially caused by the "swirled region". In model II, this region was the smallest with a relatively high velocity so additional torque was produced. The opposite situation occurred in model I which had the largest area of "swirled region" and a resulting lower power than model II. Differences in the power generated by each discs can be explained by the method of working medium delivery. Disc 1 was propelled from both sides, whereas discs 0 and 2 were only propelled from one side. The rims of the discs also contributed to power generation, but to a lesser extent (0,69 – 0,86 W). In model II, the impact of spacers is greater than in model III. Higher pressure acting on the spacer walls does not contribute to higher power.

Conclusions

The aim of the investigation presented in this paper was a numerical analysis of the outlet system geometry and its influence on flow phenomena occurring in a Tesla turbine. Geometry model was based on the dimensions of existing turbine. Three different outlet system were investigated. A mesh independence study was performed and computations were carried out for air, treated as an ideal gas, at inflow conditions of total pressure 3 bar, total temperature 303 K and rotational velocity 21000 rev/min. It was observed that working medium achieved Mach number M = 1,3. Overexpansion and overcompression occurred after the inlet duct, which, due to its non-isentropic nature, caused a decrease in generated power. In the “swirled region” which occurred between the jet and disc rims, backflows and swirls were present. Elimination of this area could contribute to an increase in the generated power. It was observed that in the rotor in model III, the pressure drop was slightly lower than in the other models. Spacer walls did not contribute significantly to power generation, but did help to organize outflow. The highest power was in case of model II and it was 17,1% higher value compared to the model of existing turbine, which indicates that there is a room for improvement. The power obtained from model III was in a relatively good agreement with the experimental data.

The outlet system is essential for optimal performance in Tesla turbine; hence, its shape should be optimised with respect to flow parameters and rotor geometry.

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