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## ENERĢĒTIKAS FIZIKĀLĀS UN TEHNISKĀS PROBLĒMAS



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*PHYSICAL AND TECHNICAL ENERGY PROBLEMS*

# SMART CITY THROUGH A FLEXIBLE APPROACH TO SMART ENERGY

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The paper provides an overview of the development trends of the smart city. Over the past decades, the trend of the new urban model called smart city has been gaining momentum, which is an aggregate of the latest technologies, intelligent administration and conscious citizens, which allows the city to actively develop, and effectively and efficiently solve the problems it is facing. Profound changes are also taking place in the energy sector. Researchers and other specialists offer a wide variety of innovative solutions and approaches for the concepts of intelligent cities. The paper reviews and analyses the existing methodological solutions in the field of power industry, as well as provides recommendations how to introduce the common platform on the basis of disparate sources of information on energy resources existing in the city as an optimal solution for developing the city's intelligence, flexibility and sustainability based on its starting conditions.

***Keywords***: *energy management, multi-energy city, smart city, smart city model, smart energy city, platformization*

## 1. INTRODUCTION

According to [1], in 1950, 30 percent of the world's population was urban. However in 2050, two-thirds of the world's population is projected to be urban. It is estimated that more than six billion people will live in urban environments, i.e., nearly 70 percent of the Earth's population and with nearly 90 percent of the increase concentrated in Asia and Africa. In recent decades, cities around the world have been experiencing in a very active form the process of transformation of the urban environment, forced to solve large-scale tasks and take serious challenges: demographic (including population aging and migration) [2], technological [3], green lifestyle [4], etc. technologies; environmental and social-economic [5]. The need to adapt cities to these processes and challenges has led to the emergence of a number of concepts and urban development strategies based on them, which can be treated as a gradual transformation of cities into a smart / intelligent city leading to more efficient urban planning and management and, ultimately, ensuring the high quality of life of the inhabitants by introducing advanced technologies, improving the environmental situation, maintaining the continuity and quality of urban life support systems.

In this process, central place is taken by the innovative development of urban infrastructure – energy, transport and communications. Scientific and technological progress in recent decades has revealed a number of fundamentally new opportunities for improving the quality of life in megacities, including the growth of population mobility, the reduction of environmental pollution, the transformation of urban space (for example, the introduction of intelligent street lighting systems, smart water or electricity metering, etc.). Especially strong progress is observed in green energy technologies: smart energy systems and renewable energy sources (RES), which can radically change the urban environment of big and small cities in the future.

It is well known that energy resources are not infinite; to solve the problem with their exhaustion, smart management of energy supply, infrastructure and energy flows is necessary. Among other systems and elements of the future, economists, environmentalists, energy specialists and engineers identify the following energy elements/components: smart household appliances, home energy management systems, building energy management systems, consumer/ prosumer, energy storage, electric vehicles and microgrids.

Currently, the well-known concept of the Smart City, presented in the form of wheel with six development vectors [6], is supplemented by the term "Smart Energy City" [7] as a city of smart energy, resource efficient, where intellectual energy is based on a variety of sources, integrated and sustainable in the general infrastructure of the city, which also contains innovative approaches to strategic planning. However, the abundance of different definitions of a smart city, as well as a lot of approaches to the interpretations of ways how a city can become smart, and different understandings of the importance of separate vectors of development do not give a clear picture of methodology or approach, which is most rational moving to the smartness.

Megapolises with a multi-million population as well as small towns, cities with developed infrastructure and just starting their way to develop intelligence, cities in warm countries and in countries with a cold climate, cities with a developed transport system and electric vehicles or lack thereof – they all want to become smart, and all they need their own methodology and ways to achieve smartness, suitable for their starting conditions.

Based on the above-mentioned considerations, this definition of "smart" city can be given: a city whose all resources are spent most effectively on the basis of the analysis of the information received from all structures, organisations and inhabitants of this city.

The paper presents an analysis of approaches to energy management and planning in smart cities, their strengths and weaknesses, as well as recommendations for the holistic and effective planning of urban development towards sustainable growth of intelligence.

## 2. ROLE OF ENERGY IN THE SMART CITY CONCEPT

Moving toward intelligent cities and improving the quality of our life in cities, we need to understand clearly, what we are speaking about. We need to keep in mind the whole concept of a smart city, its separate aspects and vectors of developing. Smart City is an urban development that unites the needs of the citizens in a sustainable and secure way along six vectors:

1. Smart Governance: Public and private organisations, transparency of city management and its infrastructures, open data.
2. Smart Economy: on the basis there are the processes that support the sustainable growth of the city, its individual parts and infrastructures.
3. Smart People: people who contribute to creativity, have critical thinking and are able to apply innovative ICT for their everyday life.
4. Smart Mobility: integrated transport and logistic systems, innovative transport solutions.
5. Smart Living: healthy and safe living through smart technologies and applications that enable responsible lifestyles, behaviour and consumption.
6. Smart Environment: sustainable increasing of renewable energy sources and green energy managed by ICT control and monitoring, waste and pollution control and smart management.

Despite the fact that the term "energy" in the above-mentioned concept is hidden, it is obvious that energy is the key to the sustainable development of the smart city as is shown in Fig. 1.

All six vectors need energy in its different forms and ways, which requires the development of its intelligent, efficient production, transformation, storage, distribution and consumption in all areas of the smart city. Therefore, it is necessary to find a way of an effective interaction between the dimensions of a smart city and the energy which participates and interacts with each of the areas of development.

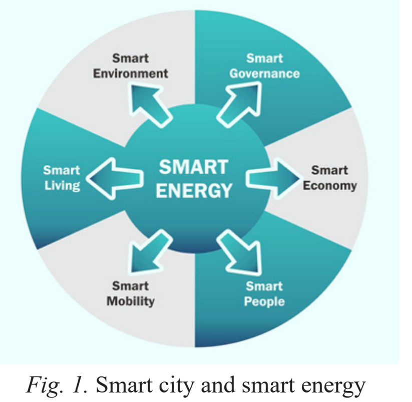


*Fig. 1.* Smart city and smart energy interaction model.

Whereas energy has the most influence on other vectors for the development of a smart city and its fundamental base, an important factor is the understanding of the clear and successful methodology for the development of smart energy in city. To streamline the approach to understanding smart energy in the city, the concept of "Smart Energy City" (SEC) has been created, which makes possible to be aware of the need for an integrated approach to energy in a smart city.

The way to develop the sustainable smart energy city is considered by [8], providing the definition for SEC, as well as giving a set of smart energy practical solutions and technologies, considering interconnections between such concepts as smart city, smart energy, sustainability and its management and stressing that interaction between these basic areas is not enough clear delineated.

A more holistic SEC definition is provided by [9]: "The Smart Energy City is highly energy and resource efficient, and is increasingly powered by renewable energy sources; it relies on integrated and resilient resource systems, as well as insight-driven and innovative approaches to strategic planning. The application of information, communication and technology is commonly a means to meet these objectives. The Smart Energy City, as a core to the concept of the Smart City, provides its users with a liveable, affordable, climate-friendly and engaging environment that supports the needs and interests of its users and is based on a sustainable economy." Such approaches to smart energy are really diversified and make clear enough the whole picture of the smart city and the role of smart energy in it.

In addition, since initiatives aimed at the effective implementation of renewable energy sources have an advantage in the development of cities, the issue of the ecological introduction and use of smart energy is more acute than ever in all spheres of city life. As stressed in [10], the transition to renewables happens all across the entire urban energy landscape from buildings to transport, industry and power. Renewables can bring tremendous benefits to cities, including cleaner air, modern services and improved living spaces. At the same time, cities are crucial to the world's transition to a low-carbon economy, accounting for 65 % of global energy use and 70 % of man-made carbon emissions. The intermittency of renewable sources, the increasing demand, and the necessity of energy-efficient transport systems, among other things, represent important energy challenges that are better addressed as a whole rather than separately, as is usually the case [11].

As a brief summary of the main points, it is necessary to mention that the concept of a smart city, including the six development vectors, covers all major interconnected areas of the city. This city model is appropriate to use for a general overview of trends, overall development planning and identifying areas required for transformation. On the other hand, the concept of smart energy city implies a more professional, more focused approach to selecting and adopting solutions that are necessary for city development, based on an integrated approach to energy issues as the most influential factor in the sustainable development of a smart city. Cities' energy requirements are complex and abundant. In consequence, modern cities should improve present systems and implement new solutions in a coordinated way and through an optimal approach, by profiting from the synergies among all these energy solutions.

The complexity of the approach to smart energy city is illustrated in Fig. 2.

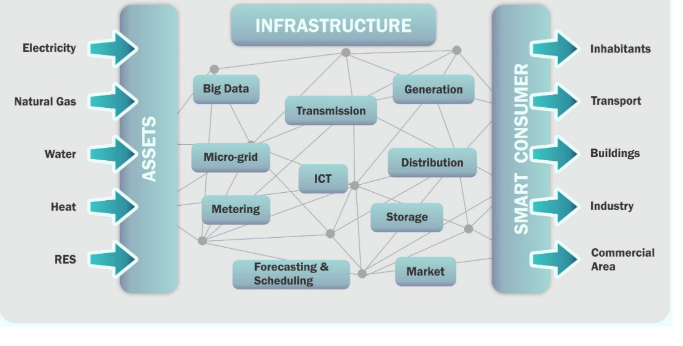


*Fig. 2.* Smart energy structure.

Between the energy sources and their final smart consumers, there is an infrastructure that includes a variety of different positions, from production and conversion of energy, to the use of ICT solutions, micro grids, and others that make energy consumption smart, economical, sustainable, meeting the needs of the environment and raising awareness of consumers and prosumers.

## 3. REVIEW OF APPROACHES TO SMART CITY

The research questions involved in transforming cities into smart cities are highly complex and can only be solved by taking an interdisciplinary, transnational approach [12].

We propose to consider different methods of the smart city dimensions. Table 1 provides an overview of approaches to modelling and developing smart energy and smart city.

*Table 1*

**Approaches to Smart City Development**

| Approach | Short description |
|---|---|
| Employment of optimisation to single sectors of development | Innovative solutions aimed to develop separate vectors and areas solving local problems. Use of indicators, city ranking, standardisation, IT-based innovation approach to create a suitable solution |
| New city planning | Methodologies with recommendations on what is needed to plan and implement any new development (smart district, smart city) |
| Development of smart energy city (SEC) | At the forefront, there is smart energy as one of the most important aspects of the development of a smart city |
| Energy hubs, multi-energy systems | Prospective development of a smart city through integrated multi-energy systems |
| Smart city infrastructure architecture model (SCIAM) | Complex approach to a smart city by considering city layers with various indicators and their interactions |
| Blockchains | Applicable to smart city, the blockchain is the right network to succeed in the delivery of codes (policies, planning, regulations and standards) since it is universal and decentralised, allowing for a bottom-up delivery of codes owned and implemented by the citizen and not by a central authority. |
| Platformization | Unification of disparate resources of a smart city on the platform basis |

A large group of methods and approaches concentrate on making a study, planning and development of smart cities in a gradual, step by step, improvement of each city sphere, moving toward smartness. The article [13] considers energy-intervention areas within the city and their relations, as well as compares different currently available energy models, energy-efficient facilities, control systems, and demand-response schemes. The paper [14] explores the relations existing among urban and territorial networks, actors and stakeholders, functions and activities, suggesting a way to integrate various aspects of a smart city.

An approach called Smartainability, with the help of quality and quantitative indicators, assesses the extent to which enabling technologies for intellectual solutions contribute to improving energy efficiency and environmental sustainability in the city [15]. Thus, the presented group of studies offers options for moving towards smart city, starting with the selection of a separate area of development, for example, an increase in the efficiency of electricity use in smart buildings, or decision to cut traffic congestion in the city, etc., till planning simultaneous implementation of effective solutions in various areas. It is also proposed to use indicators, standards, comparison of development indicators and the rating of cities to determine the areas with the greatest need for improvement.

Another group of smart city studies argues that the most optimal solution is the planning of separate regions, districts or even a whole city in advance by including in the plan all the necessary infrastructure and possibilities for smart building and using smart technologies of a smart city. It is claimed that cities generally have no clear idea as to their precise future smart city requirements at the present time, and specify few models in order to effectively meet potential future requirements, and give guidance on what is needed to plan for any new development to support the smart city plans for a chosen area [16].

Some authors focused on the issues of smart city through the prism of smart energy, believing that energy management is the most influential means of developing smart cities [8], [17]. The overall approach of the Sustainable Urban Regeneration Model [18] describes an approach to the Sustainable Urban Regeneration Model, stressing that cities need to become 'smarter' with respect to energy optimisation. The added value of the proposed methodology lies in the combination of energy efficiency and energy management using multidisciplinary data sources.

Another area of consideration of smart city issues, which has become very relevant in the past few years, is the use of energy centres (energy hubs) for the optimisation and efficient management of energy flows throughout the city. The use of various models, including energy hubs, as well as the possibility of their use for different conditions and needs of the city, its flexibility and management is considered in [19] and [20]. In [21], the idea is discussed that a smart city can be considered to be an open complex giant system, from which consensus emergence can be demonstrated and handled by meta-synthesis method, and clarify the differences between smart city management and traditional city management.

An example of considering a city as a multi-dimensional system and an approach to modelling solutions through the construction of a model for each layer is presented in smart city infrastructure architecture model (SCIAM) [22].

In recent years, one more approach has become increasingly popular and topical – the so-called blockchain technology – a continuous sequential chain of blocks, containing information built according to certain rules. Most often, copies of blockchains are stored independently of each other (extremely parallel) on a variety of different computers. The technology of blockchains can be extended to any interconnected information blocks. The source [23] expresses assurance that the blockchain networks will disrupt the urban context as well, similarly to what is happening with the previous application domains, and put forward Future Living Framework as the meta use case of a wide research called Blockchain4Cities. The benefits of using blockchain in the urban field was shown. "Blockchain is here to take on and be the next network for cities." Article [24] discusses a model for service the prosumers using blockchain technology, which allows connecting different sources of energy to different users and manufacturers. Analysing the energy picture of users, the authors argue that this technology leads to increased energy efficiency. Blockchain technology and energy issues are combined to integrate the power and information infrastructure.

Platformization – a holistic approach to smart city vision – will be described in more detail in the further section of this paper.

According to the above-mentioned considerations, there are many approaches to consider smart cities, which we tried to classify. Each of them has a right to exist, and was developed based on a certain vision of an intelligent city. Based on these different visions, methodologies and tools for achieving smart results were developed. Can we consider the development of one particular area or the solution of one particular task a result? Of course, yes. However, a smart city is the widely branched infrastructure with multiplicity of functions and multivariate conditions for their interaction. Therefore, we believe that some of the approaches to the development of a smart city are better suited for a holistic transformation of the city into an intelligent one, while the other approaches to a less degree serve this purpose.

## 4. SMART SOLUTION FOR CITY STRIVES FOR INTELLIGENCE

In the forefront of the city development, there are multidisciplinary methods and innovative decisions of production, transmission, accumulation and consumption of energy resources, with the purpose to optimise the already existing technologies and equipment, and there are approaches to flexible switching to new, such as mini-generators, micro-grids and the use of the energy of wind, sun, hydrogen and renewables.

Emiliano Dall'Anese, Pierluigi Mancarella, and Antonello Monti in [19] consider energy production-transforming-storing-consumption aspects with the so-called hubs – the energy centres. By means of hubs it is suggested to solve a problem of delivery and consumption of energy resources, such as electricity, gas, water, district heat, etc. Nowadays, the policy of decarbonisation is on the top, as well as implementation of production and electricity consumption from small generation from renewable energy sources. Therefore, the increasing relevance is acquired by the need to shift supply of energy resources and their consumption, e.g., by means of energy accumulation, or a pre-discretion of additional power sources. Energy centres (hubs), depending on the needs of a network and load consumption, can have a variety of inputs/outputs and conversion stages, along with the storage of different energy types. Relevant optimisation problems can be used to compute the optimal energy mix for the hub to minimise operational costs or to optimise the operation of an interconnected system of energy hubs.

The principal advantage of such a system is its flexibility, as well as an ability to use energy resources economically and operationally; it is trouble-free in deliveries taking into consideration the possibilities of energy producers and consumer demands for different types of energy.

The examples of transmission-level and distribution-level modelling and applications were considered, stressing that the new approach to multilevel energy flexibility could be available in gas, electricity, heat and water networks through emerging technologies that could be accounted for in the development of integrated optimisation and control strategies considering not only potential flexibility benefits but also relevant flexibility constraints.

This picture is not complete without citizens or local residents, who are supposed to participate in the innovation process through platforms.

Platformization is also a relatively new trend in the development of the infrastructure and the city as a whole. Since all the advantages of smart cities with new technologies, devices and approaches to solving problems arising in cities are associated with people living in them, with their awareness and willingness to promote city development, efficiency and care of the environment, special attention should be paid to creating the opportunity for citizens directly participate in the life of the city, managing its processes and actively influencing all structures. The issues [25], [26] and [27] raise problems of the effectiveness of the development of any city through the creation of a common infrastructure through open data in the form of a platform where multiple sources of information from all over the city, its most important functions and objects are collected. This approach to the development of the city, based on the human resource, raising awareness of citizens, the perspective of transforming consumers into prosumers, deserves close attention in the perspective and current trends in energy, transport, ICT and other areas.

Platformization means the unification of disparate sources of information, for example, in the case of energy, the production, distribution and sale of electricity and heat, the supply of gas, hot water, the weather forecast, the price of energy services offered by various sellers, the forecast of the cost of electricity on the exchange, the data concerning customers' consumption of electricity, and much more, gathered under one "roof" – on the basis of a common platform, where data from each information source are collected and constantly updated.

Unlike solutions based on the introduction of more and more advanced technologies to enhance the city's intelligence, the work [25] proposes a way to achieve an intelligent and sustainable city by combining existing infrastructure, i.e., open government data and data from large energy companies and sensory networks deployed in cities, by providing a mechanism for sharing the heterogeneous data sources offered by the city, which reduces the complexity of access to city data while bringing citizens closer to the role of prosumer and allowing for integration of data into the city's ecosystem.

As stressed in [28], an open data portal is the gateway to a city's open data resources. The open data portal becomes a progressive way, through which the city can provide its citizens and specialists with extensive data concerning economy, management, as well as special areas such as energy, transport, buildings, etc. Besides, it would be good practice to maintain an open data portal independent of the control of city authorities, large management companies and other interested parties. Open access to data is the right of all citizens of the city. Raising the awareness of citizens by keeping them informed allows the city to have the opportunity to make serious and qualitative steps towards enhancing the effectiveness, sustainability of all indicators and actions performed in it. The more open data from different areas of functioning are available, the more opportunities are available for a diverse combination of them, the more effectively and powerfully the combined platform performs its functions, the more professionals and residents will turn to it to solve their problems, the greater the consensus can be found in resolving any issue related to the topic of a smart city.

Thereby, an acceptable way to reach flexibility is to organise an open and protected data space such as a smart platform, including an ordered data structure from multiple sources such as energy producers, distributors and sellers of energy resources, the data from consumers and prosumers, as well as possible additional sources of useful information, e.g., weather forecast, data from the electricity exchange at the moment, its statistics by month and by year etc. The examples of such platforms can already be seen in many European countries, e.g., [29] (Estonia), [30] (Denmark), [31] (Norway), [32] (Austria).

Open data allows expanding the management and development of smart cities, including among others the possibilities of navigating open data sources, transparency and accountability, performance management, transportation and infrastructure, resilient city planning, IoT of smart cities, civic engagement, etc.

## 5. CONCLUSIONS

Small and large cities collect a huge amount of information about what is happening to them. Much of this information has been collected over the years, and some of it is available for public review. Nevertheless, to work effectively, we need more than some separate resources we can find on the Internet, for a fee or without it to get acquainted with certain information, for example, on energy consumption, or the possibility of using different tariff plans for electricity consumption, etc. By unlocking data and making them open with the help of a common data platform, we can achieve much greater efficiency in managing resources, increasing citizen awareness and ultimately in accelerating the development of each city towards its sustainability and intelligence.

Leading experts in a smart city theme believe that energy, transport and information and communication technologies are the key challenges for the further development of smart cities. Electricity, natural gas, water and district heating systems are predominantly planned and operating independently from each other. However, it is getting recognised more and more that integrated optimisation and control of these resources will make it possible to achieve greater efficiency and environmental benefits. Integrated actions across multiple infrastructures can balance costs while increasing safety and access to energy (both by limiting greenhouse gas emissions and by optimising the use of natural resources).

It is evident that nowadays energy solutions based on a rigid, non-variant approach to the production, distribution and consumption of resources or using the data have lost their relevance. The urban environment of modern cities requires a different approach based on flexibility, the possibility of combining different spheres, services and proposals, as well as the ability to control and manage infrastructures with high speed of response and making the right decisions.

The viability of any system is determined by its flexibility, i.e., the ability to timely and adequately respond to any tasks that have arisen in connection with the system during its operation. Another crucial feature is the ability to solve issues related to its functioning in a comprehensive manner, making the right decisions not only based on the current situation but also taking into account the prospects for the development of this and neighbouring areas. Such a system can develop steadily and purposefully in any circumstances, flexibly adjusting to the changes that have occurred. It is the qualities a smart city needs now most of all.

Based on the above-mentioned considerations, a conclusion can be made regarding the topic under consideration, i.e., smart energy in a smart city. The creation of a unified open data platform based on numerous sources of energy and related information will make it possible to develop a smart energy city in an efficient, sustainable, economically viable and environment-friendly way to promote active involvement of citizens in the life of the city and contribute to its intelligence.

The complex approach to solving the multivariate questions of the development of a smart city is undoubtedly in the collection of all the data of a smart city (big data) into a unified platform. This would allow solving at once many tasks on the way to the formation of an intelligent city, at whatever stage of development it is now. These tasks are the efficient and rational use of energy resources, the transparency and accessibility of data, the increase in citizens' awareness through their active involvement in the management of the city and its resources, as well as solving transport problems, reducing CO2 emissions and introducing green energy sources into the urban environment.

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## VIEDĀ PILSĒTA: ELASTĪGA PIEEJA VIEDAI ENERĢIJAI

A. Mutule, J. Teremranova, N. Antoškovs

### Kopsavilkums

Pēdējo desmitgažu laikā arvien populārāks kļūst jaunais pilsētvides attīstības modelis, saukts par "viedo pilsētu", kas ir jaunāko tehnoloģiju konglomerāts, kā arī inteliģenta un apzināta pārvaldība un dzīvesveids, kas ļauj pilsētai efektīvi attīstīt un risināt problēmas, ar kurām tā saskaras.

Milzīgas pārmaiņas notiek arī pilsētu enerģētikas nozarē; pētnieki un citi speciālisti piedāvā visdažādākos inovatīvus risinājumus un pieejas viedo pilsētu koncepcijām. Raksts ir veltīts esošo metodisko risinājumu pārskatīšanai un analīzei enerģētikas jomā, kā arī ieteikumi apsvērumu apskatei kopējās platformas ieviešanai, pamatojoties uz esošajiem pilsētas atšķirīgajiem informācijas avotiem par enerģijas resursiem. Šajā rakstā tiek pētītas "viedo pilsētu" attīstības tendences un pieejas, ir piedāvāti optimālie risinājumi pilsētas elastīgas un ilgtspējīgas attīstībai.

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# OPTIMISATION OF COMBINED CYCLE GAS TURBINE POWER PLANT IN INTRADAY MARKET: RIGA CHP-2 EXAMPLE

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In the research, the influence of optimised combined cycle gas turbine unit – according to the previously developed *EM & OM* approach with its use in the intraday market – is evaluated on the generation portfolio. It consists of the two combined cycle gas turbine units. The introduced evaluation algorithm saves the power and heat balance before and after the performance of *EM & OM* approach by making changes in the generation profile of units. The aim of this algorithm is profit maximisation of the generation portfolio. The evaluation algorithm is implemented in multi-paradigm numerical computing environment *MATLab* on the example of Riga CHP-2. The results show that the use of *EM & OM* approach in the intraday market can be profitable or unprofitable. It depends on the initial state of generation units in the intraday market and on the content of the generation portfolio.

***Keywords:*** *conventional generation, EM & OM approach, generation portfolio, intraday market*

## 1. INTRODUCTION

Nowadays problems of conventional generation are discovered in many literature sources [1], [2], [3], [4], [5], i.e., the shifting from the base load operation to the cycling operation. Combined cycle gas turbine (CCGT) technology is partly adapted to new running conditions [6], [7]. There are a lot of measures [8] to increase the flexibility of power plants from expensive [9], [10] to cost-neutral, for example, by applying the *EM & OM* (evaluation model & optimisation model) approach developed and presented by the authors in [11] to optimise the cycling operation of CCGT power plants.

In brief, the EM & OM approach consists of the two models, i.e., EM and OM. The first processes the production data of power plant and consequently determines the cycling characteristics of power plant and inputs for OM. The second ensures the extension of cycling operation range by shifting shutdown "forward" and start-up "backward" and, hence, the added electricity is produced, the numbers of cycling periods are reduced and start-ups are replaced with less adverse ones. In [11], the authors proposed that the EM & OM approach could be used in different Nord Pool physical markets: day-ahead, intraday or real time/balance market, but its performance changes depending on the type of physical market (Table 1).

*Table 1*

**The Performance of *EM & OM* Approach in Different Nord Pool Physical Markets**

| Parameter | Type of market | | |
|---|---|---|---|
| | Day-ahead market | Intraday market | Balancing market |
| Benefits of using the *EM & OM* approach | The integration of approach in power plant optimisation models to prepare the bids for submission in the market. The accuracy of optimisation models is increased and the planning of conventional generation operation becomes more precise and profitable because the features of start-ups and proposed principles of cycling operation improvement are taken into consideration. | The observation of cycling operation features and the proposed principles of its improvement provide more profitable operation of conventional generation, when bids are approved | The consideration of start-up features and the proposed principles of cycling operation improvement ensure the possibility to evaluate the production of additional energy in areas with power deficit. |
| The necessity of added calculations | The forecast of input data (ambient temperature, heat load, electricity price, etc.) | Investigating the impact on other generation units (portfolio) | Investigating the impact on other generation units (portfolio) |

In [11], the developed *EM & OM* approach was verified on the example of CCGT-2/1 of Riga CHP-2 (the detailed information about this power plant is available in [11], [12]) on the principles of Nord Pool intraday physical market. It is when the results of unit commitment (UC) and electricity price are known, i.e., the dashed box in Fig. 1. $Y'^1$ denotes the first cogeneration unit and $Y'^2$ – the second cogeneration unit of generation portfolio *Y'*, which is Riga CHP-2.

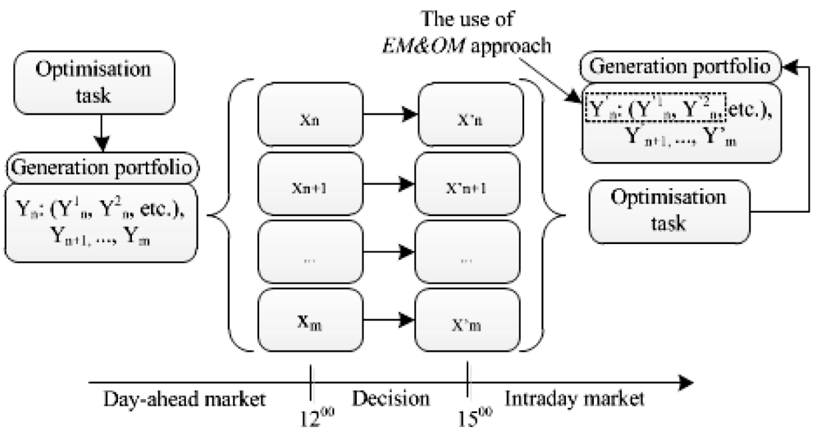


*Fig. 1.* The example of use of the *EM & OM* approach in [11].
($Y_n$, $Y_{n+1}$, $Y_m$ denote the generation portfolio before bid submission to the Nord Pool market; $x_n$, $x_{n+1}$, $x_m$ – the submitted bids to the market; $x'_n$, $x'_{n+1}$, $x'_m$ – the approved bids on the Nord Pool market; $Y'_n$, $Y'_{n+1}$, $Y'_m$ – the generation portfolio after bid approval on the Nord Pool market and optimisation provision in line with the approved bids)

According to Table 1, if the *EM & OM* approach is used in the intraday market, then the added calculations are needed, which are presented in this paper. The influence of the optimised generation unit should be investigated on other generation units or portfolio.

In [11], the impact of optimised CCGT-2/1 cogeneration unit on the generation portfolio, i.e., Riga CHP-2, was omitted. That is why in this article the authors assess this impact by introducing the evaluation algorithm, which consists of the CCGT-2/2 optimisation according to the *EM & OM* approach and changes of cogeneration units' (CCGT-2/1 and CCGT-2/2) generation portfolio in multi-paradigm numerical computing environment *MATLab.*

The remaining part of this paper is organised as follows: in Section 2 the assessment algorithm is presented; in Section 3 the results of assessment are provided; in Section 4 the main conclusions are made.

## 2. THE EVALUATION ALGORITHM

The evaluation algorithm is created for thermal power plants, which consist of the two CCGT units (Fig. 2).

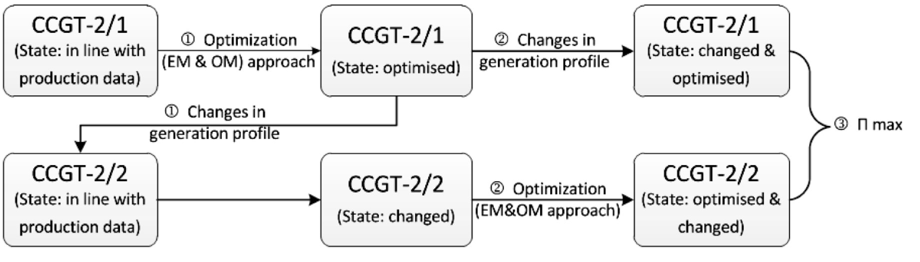


*Fig. 2.* The block scheme of the evaluation algorithm.

Initially, the operation of CCGT-2/1 unit is optimised in line with the *EM & OM* approach. Additionally, the produced power and heat energy by the first cogeneration unit are compensated by CCGT-2/2 unit, i.e., the changes in CCGT-2/2 generation profile are observed. Then the *"changed"* generation profile of CCGT-2/2 unit is optimised by the *EM & OM* approach making changes in CCGT-2/1 optimised profile. As both units are identical, the obtained characteristics of CCGT-2/1 in [11] are used to provide the calculation with CCGT-2/2.

The optimisation of CCGT-2/2 unit in line with the *EM & OM* approach is provided and/or changes in the generation portfolio of CCGT-2/1 are implemented, if it is possible to ensure them. For example, the second unit is operated in parallel with the first unit, the load of cogeneration units is enough to make changes in the generation portfolio, it is possible to save the power and heat balance, etc.

The objective function of the evaluation algorithm is profit (Π) maximisation of Riga CHP-2:

$$\sum_{i=1}^{i=k}\left( \Pi'_{CCTG-2/1_i} - \Pi_{CCGT-2/1_i}\right) + \left(\Pi'_{CCTG-2/2_i} - \Pi_{CCGT-2/2_i}\right) \rightarrow \max \Pi$$

Subjected to

$i = 1,...k\ ;\ i \in Z_+$

$P_{CCGT-2/1}^{min} < P_{CCGT-2/1} \le P_{CCGT-2/1}^{max}$

$Q_{CCGT-2/1}^{min} < Q_{CCGT-2/1} \le Q_{CCGT-2/1}^{max}$

$P_{CCGT-2/2}^{min} < P_{CCGT-2/2} \le P_{CCGT-2/2}^{max}$

$Q_{CCGT-2/2}^{min} < Q_{CCGT-2/2} \le Q_{CCGT-2/2}^{max}$

$\sum_{i=1}^{i=k} P_{1i} = \sum_{i=1}^{i=k} P_{2i}$ Electrical power balance. $P_1$ is the sum of CCGT-2/1 and CCGT-2/2 electrical power in line with the production data. $P_2$ is the sum of CCGT-2/1 and CCGT-2/2 electrical power in the changed and optimised states, respectively.

$\sum_{i=1}^{i=k} Q_{1i} = \sum_{i=1}^{i=k} Q_{2i}$ Heat power balance. $Q_1$ is the sum of CCGT-2/1 and CCGT-2/2 heat power according to the production data. $Q_2$ is the sum of CCGT-2/1 and CCGT-2/2 heat power in the changed and optimised states, respectively.

where

| | |
|---|---|
| $\Pi_{CCGT-2/1_i}$ | profit of the first cogeneration unit according to the production data, [€]; |
| $\Pi'_{CCTG-2/1_i}$ | profit of the first cogeneration unit in the changed state, [€]; |
| $\Pi_{CCTG-2/2_i}$ | profit of the second cogeneration unit in line with the production data, [€]; |
| $\Pi'_{CCTG-2/2_i}$ | profit of the second cogeneration unit in the optimised state, [€]; |
| $i$ | number of cycling operation ranges, [number]; |
| $P$ | electrical power, [MW]; |
| $Q$ | heat power, [MW]. |

The profit of cogeneration units is calculated taking into account the marginal costs of cogeneration units, which hold on two components: natural gas and carbon dioxide.

## 3. RESULTS OF EVALUATION ALGORITHM

Figure 3 presents the example of evaluation algorithm performance results. In line with the *EM&OM* approach, the start-up of CCGT-2/1 was shifting to 15 hours backward. The start-up time was at 0.00 instead of 15.00. Due to high electricity price, in this period (from 0.00 to 15.00) the electrical power of CCGT-2/1 was higher by 50 MW then after 15.00. To save the power and heat balance of Riga CHP-2, the power of the CCGT-2/2 was reduced until the technical minimum, i.e., 149 MW.

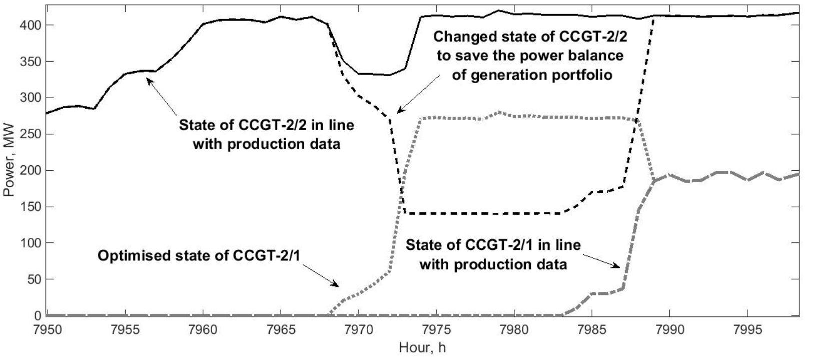


*Fig. 3.* The example of evaluation algorithm performance results.

In line with the evaluation algorithm (Fig. 2) after the optimisation of CCGT-2/1 and changes of CCGT-2/2 generation profile, the optimisation of CCGT-2/2 and changes in the optimised CCGT-2/1 profile should be performed. According to the reflected situation in Fig. 3, they were not done because there were not any possibilities.

In [11], the *EM & OM* approach was performed simultaneously for start-ups and shutdowns. In the present research, this approach is divided into the three scenarios:

- Scenario No. 1: Start-ups are shifted *"backward"*;
- Scenario No. 2: Shutdowns are shifted *"forward"*;
- Scenario No. 3: Start-ups are shifted *"backward"* and shutdowns – *"forward"*.

The results of the three scenarios of the *EM & OM* approach in line with the evaluated algorithm in Fig. 3 are presented in Table 2. The positive result is obtained in Scenario No. 1, i.e., additional profit at the value of 23 800 € for added 24 operation hours. The last two scenarios (Scenarios No. 2 and No. 3) ensure an increase in operation hours by 29 and 59 hours, but provide a negative profit in monetary terms by - 102 600 € and - 78 600 €, respectively.

*Table 2*

**Interpretation of Optimisation Results**

| **Parameters & Scenarios** | **The value of parameter before optimisation** | **The value of parameter after optimisation** | **Additional profit** |
|---|---|---|---|
| **Scenario No. 1:** | **Start-ups are shifted *"backward"*** | | |
| Gain/Losses, [€] | $17{,}2537\cdot10^6$ | $17{,}2775\cdot10^6$ | 23 800 |
| Operation hours of both cogeneration units, [h] | 5 744 | 5 768 | 24 |
| **Scenario No. 2:** | **Shutdowns are shifted *"forward"*** | | |
| Gain/Losses, [€] | $17{,}2537\cdot10^6$ | $17{,}1511\cdot10^6$ | - 102 600 |
| Operation hours of both cogeneration units, [h] | 5 744 | 5773 | 29 |
| **Scenario No. 3:** | **Start-ups are shifted *"backward"* and shutdowns – *"forward"*** | | |
| Gain/Losses, [€] | $17{,}2537\cdot10^6$ | $17{,}1751\cdot10^6$ | - 78 600 |
| Operation hours of both cogeneration units, [h] | 5 744 | 5803 | 59 |

In case of Scenario No. 1, the additional profit is obtained due to the reduction of time spent in warm state preservation. This has resulted in more efficient start-up. In their turn, Scenarios No. 2 and No. 3 provide a negative profit because the optimisation of CCGT-2/1 has led to the CCGT-2/2 power reduction to the technical minimum. The specific natural gas consumption of the second cogeneration unit has increased. As a result, the efficiency of CCGT-2/2 has decreased.

## 4. DISCUSSION

In the present research, the authors have evaluated the impact of the optimised CCGT unit running condition in line with the *EM & OM* approach in intraday market on the generation portfolio. For this reason, the evaluation algorithm has been introduced with the optimisation task: profit maximisation of the generation portfolio. The *EM & OM* approach has been implemented according to the evaluation algorithm by saving the power and heat balance of the generation portfolio, i.e., making changes in the generation profile of units.

The evaluation algorithm has been implemented on the example of Riga CHP-2. In line with the obtained results, it can be concluded that the use of the *EM & OM* approach in the intraday market can be both efficient and inefficient, i.e., with additional profit or losses, respectively. The authors consider that the positive result (additionally gained profit) of the *EM & OM* approach use in the intraday market can be achieved by extending the generation portfolio and adding a different generation unit, for example, natural gas and hydropower units.

## *ACKNOWLEDGEMENTS*

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## KOMBINĒTĀ CIKLA GĀZES TURBĪNAS ELEKTROSTACIJU DARBĪBAS REŽĪMU OPTIMIZĀCIJA TEKOŠĀ DIENAS TIRGŪ: RĪGAS TEC-2 PIEMĒRS

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K o p s a v i l k u m s

Šajā darbā tiek apskatīta optimizētās – pēc iepriekš izstrādātās *EM & OM* pieejas tekošās dienas tirgū – TEC-2 divu energobloku (katrs no tiem sastāv no divām kombinētā cikla gāzes un tvaika turbīnām) ietekme uz ražošanas portfeli. Piedāvātais vērtēšanas algoritms saglabā elektriskās un siltuma jaudas bilanci pirms un pēc *EM & OM* pieejas pielietošanas, mainot energobloku ražošanas profilu. Vērtēšanas algoritma mērķis ir ģenerācijas portfeļa peļņas palielināšana. Tas tiek realizēts uz objektu orientētas programmēšanas valodas – *MATLab* - uz Rīgas TEC-2 piemēra. Iegūtie rezultāti atspoguļo, ka *EM & OM* pieejas pielietošana tekošā dienas tirgū varbūt efektīva, neitrālā vai neefektīva. Iegūtā rezultāta vērtība ir atkarīga no ražošanas iekārtu sākotnēja stāvokļa tekošā dienas tirgū un apskatītā ģenerācijas portfeļa sastāva.

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# CONSISTENCY ANALYSIS AND DATA CONSULTATION OF GAS SYSTEM OF GAS-ELECTRICITY NETWORK OF LATVIA

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In the present research, the main critical points of gas transmission and storage system of Latvia have been determined to ensure secure and reliable gas supply among the Baltic States to fulfil the core objectives of the EU energy policies.

Technical data of critical points of the gas transmission and storage system of Latvia have been collected and analysed with the SWOT method and solutions have been provided to increase the reliability of the regional natural gas system.

***Keywords****: Baltic countries, capacity of pipelines, critical points, reliability, gas storage system, security, gas transmision system*

## 1. INTRODUCTION

To achieve long-term state and energy strategic goals, one of the basic conditions is diversification of energy sources and security of energy supplies. For a long time, the core objectives of the EU energy policies are competitiveness, sustainability and security of supply. In February 2015, the EU Commission launched work on the European Energy Union. Security of supply is defined as one of five European Energy Union's strategy vectors. Natural gas takes an essential part in the EU energy balance as it makes approximately 25 % of primary energy source consumption, and it is used mainly for electricity [1].

Natural gas is an important resource for the Latvian economy and energy system, and it plays an important role in the energy conversion sector – production of heat and electricity. The largest consumer of natural gas in Latvia is JSC Latvenergo, which uses natural gas mainly for combined heat and power production. Thus, disruptions in natural gas supply system would impact both the industrial and household sectors. Natural gas supply is one of the national security issues. That is why security of natural gas supply and the necessity of more precise assessment of risks of possible disruptions become increasingly acute. In the assessment of natural gas supply system security, security standards of the EU natural gas supply system are used in Latvia. Still these standards do not cover, to a full extent, the specifics of the Latvian situation [2], [3].

## 2. THE LATVIAN GAS – POWER SUPPLY SYSTEM AND ITS DEVELOPMENT PROSPECTS

JSC "Conexus Baltic Grid" (founded in 2017) ensures operation for Incukalns underground gas storage, a gas transmission pipeline system with an overall length of 1191 km, a gas distribution pipeline system with an overall length of 4950 km, comprising a network of natural gas pipelines, gas regulation devices, and electrical protection devices. Latvia's natural gas transmission infrastructure is part of the natural gas transmission system of the Baltic States. The existing intercountry natural gas transmission system makes it possible to receive natural gas via intercountry gas transmission pipelines. Supply of natural gas in the direction from Pskov to Riga is ensured via two parallel gas pipelines, between which there are connecting lines [4], [5].

Since 2000, medium-pressure ($P < 0.01$ MPa; $P < 0.4$ MPa) distribution pipeline systems have been built in individual dwelling areas and high-pressure ($P < 1.6$ MPa) distribution pipeline systems in industrial territories, which can ensure the operation of potential micro cogeneration and cogeneration units from the existing distribution pipeline system. 65 million EUR have been invested into the construction of new gas distribution pipelines, building 4950 km of distribution pipelines, providing connections for 40.85 thousand clients, which makes up approx. 50 % of all the possible connections to the newly built distribution system. Figure 1 shows the existing gas system [4]–[7].

Over the past 15 years, the most considerable number of applications and, consequently, connections have been observed in the territories of Riga region – Marupe, Kekava, Carnikava, Stopini, Adazi, Olaine, Jurmala –, where the largest investments have been made into the development of the distribution network. In 2014, new connections were built for 1211 clients; capacity was increased for 435 clients, thus connecting or increasing capacity for 1646 clients in total. In 2014, 31.3 km of new distribution system pipelines were built, with total investments of 1.2 million EUR [6]–[9].

The structure of the new connections made in 2016 is as follows: individual houses – 69 %, industrial clients – 12 %, commercial clients – 9 %, and flats – 10 %. The transmission system ensures complete natural gas supply for the country's major cities, considering the existence of the connecting joint between the transmission joint, namely, the transmission capacity reserves of the gas-regulating stations. Natural gas sales in 2016 compared to 2015 decreased by 9.45 % (in absolute terms 120 000 000 $m^3$) [6], [7].


*Fig. 1.* The existing gas system.

As regards the development of the natural gas infrastructure, it is necessary to take account of the limited natural gas market of the Baltic States and, hence, the repayment potential of the project if there is no investment support. In order to ensure energy independence regarding natural gas deliveries, a number of important interconnection infrastructures in the Baltic region were identified within BEMIP for the PCI list, for example:

- Gas Interconnector Poland–Lithuania (GIPL);
- Improvement of the Latvia–Lithuania gas interconnection;
- The regional LNG terminal;
- Enlargement and modernization of Incukalns UGS;
- Improvement of the Latvia–Estonia gas interconnection [3], [8].

Figure 2 shows the distribution of the natural gas supplied from Incukalns UGS among the consumers of the three Baltic States and Russia in the time period from 2000 till 2014. In this period, the bulk of the natural gas from Incukalns UGS was supplied to Latvia, Lithuania, Estonia, and Russia. Incukalns UGS has the potential of being enlarged in the future, thus storing a larger amount of gas. The amount of stored active gas can be increased from 2.32 billion m$^3$ to 2.6...2.8 billion m$^3$. After enlargement, also the amount of natural gas supplied to and from the storage is to increase from 28...30 billion m$^3$/day to 34...35 billion m$^3$/day.

Apart from Incukalns UGS, in Latvia there are also other sites that can potentially be used for storing natural gas. These may acquire additional significance after interconnections with the EU networks have been built. The issues of UGS availability and sufficiency in the region are important, since UGS considerably improve the reliability of natural gas supply and make it possible to regulate the supply of gas depending on the season. Of Latvia's potential UGS, Dobele underground structure has been investigated in the greatest detail and has been acknowledged a suitable site for natural gas storage. Within a project co-financed by the EU, it was acknowledged that, if a UGS were built in Dobele structure, it would rank among the EU's largest UGS in terms of capacity [3], [5], [10].

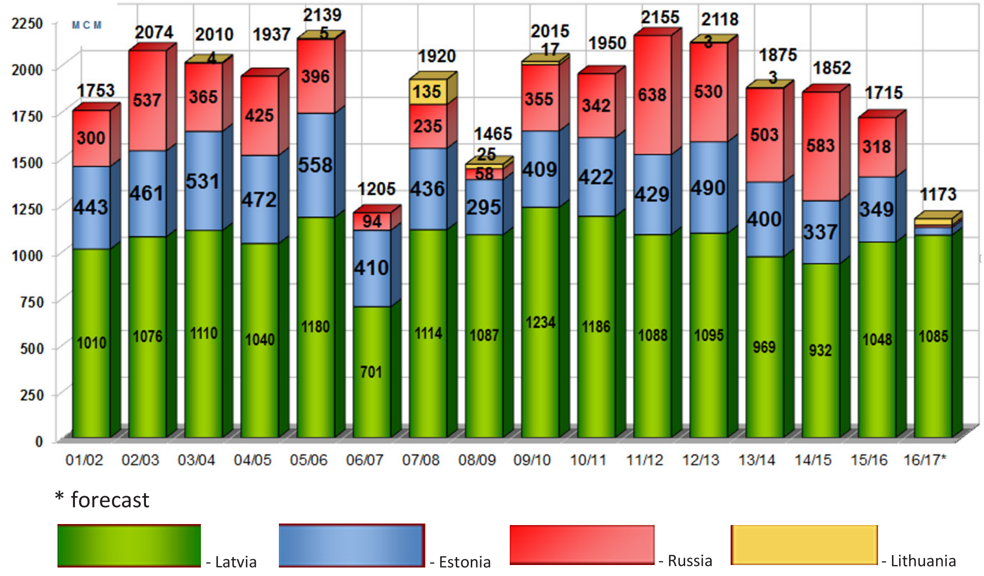


*Fig. 2*. Natural gas supply from Incukalns UGS in 2000–2014, millions m³.

In 2014, the share of natural gas in the total consumption of primary energy resources was 24.4 %. In Latvia, natural gas is mainly used for producing electricity and heat. In order to encourage the diversification of natural gas supply paths and sources as well as the emergence of a natural gas market, BEMIP states a list of the required infrastructure entities, which foresees the construction of the Gas Interconnector Poland–Lithuania as well as the improvement of the Latvia–Lithuania and Latvia–Estonia interconnections and the modernization and enlargement of Incukalns underground gas storage, which will increase the natural gas supply reliability and stability in the region [3], [11]–[14].

Uninterrupted operation of the natural gas infrastructure has to be ensured at all levels, yet primarily on a regional scale. The situation when critical disturbance arises in one major element of the gas supply infrastructure is characterised by the infrastructure safety indicator (criterion) N–1. If this criterion in the region is equal to at least 100 %, then in the case of some disturbance in this element, the natural gas deliveries can be organised in such a way as to avoid any natural gas supply limitations. In the Baltic States, the N–1 criterion is 145.94 %, provided that gas is available at Incukalns UGS. In case of calculating the N–1 criterion, only the capacities of the natural gas supply system entrance points are taken into account. Figure 3 shows natural gas supply to the Baltic States in summer and Fig. 4 – in winter [15]–[17].

Power transmission system in Latvia operated by JSC Augstsprieguma tikls consists of 330 kV and 110 kV transmission lines and substations located throughout the entire territory of Latvia, ensuring operation, maintenance and repairs of substations and devices set by distribution points, as well as is engaged in further development of the company. Latvian transmission network receives electricity from hydroelectric and thermal power stations of Latvia, as well as Lithuania and Estonia and transfers it further to the companies of distribution networks [2], [15], [18], [19].


*Fig. 3*. Gas supply to the Baltic States in summer.


*Fig. 4.* Gas supply to the Baltic States in winter.

19 electricity clients are directly connected to the transmission network in Latvia, including 5 thermal power plants (4 CHP-s and 1 Biomass) with total installed capacity of approx. 1050 MW, 3 hydro power plants located on the Daugava River with total installed capacity of approx. 1550 MW, 1 wind farm, 4 major customers and 6 distribution network operators [11], [20], [21].

Transmission network in Latvia consists of 6 connections with neighbouring countries: 2 synchronized AC (alternative current) connections with Estonia, 4 AC connections with Lithuania and 1 AC connection with Russia. The 330 kV transmission network is a very significant network not only at the Latvian level but also at the international level. 330 kV transmission network connects the Latvian power system with neighbouring power systems of Estonia, Lithuania and Russia, receives the produced electrical energy from the biggest hydro plants (Plavinas HPP and Riga HPP) and from 2 combined heat power plants (Riga CHP1 and Riga CHP2) in Latvia, as well as from energy producers in Estonia, Lithuania, Russia and Nordic countries and delivers it to lower voltage networks. 330 kV transmission network provides a reliable corridor for transit of electrical energy through the Latvian transmission network from the Baltic and Nordic countries. Through 330 kV autotransformers, electrical energy is delivered to the 110 kV transmission network. The 330 kV transmission network in Latvia is a middle node of the Baltic power systems between North and South parts. All 330 kV substations are supplied from at least two sides, the exemption is 330 kV substation in Daugavpils, which is connected to 330 kV transmission network from one side, but with two 330 kV transmission lines which could be considered the highest reliability in comparison with 1 line. Due to security of supply reasons, all 330 kV substations are with 2 autotransformers, and in emergency or repair modes of one autotransformer the second will provide all substation power to lower voltage [11], [15], [21].

110 kV transmission network in Latvia is a local network, which provides electrical energy supply for the state regions, big cities, distribution networks and directly to the energy consumers connected to the transmission network. The 110 kV transmission network is constructed as a ring scheme network and almost all 110 kV substations are connected to the transmission network at least from 2 sides, which significantly improve power supply reliability. Due to security of supply reasons, in the main part of 110 kV substations the two transformers are installed, because in emergency or repair modes of one transformer the second will provide all substation power to lower voltage. The Latvian transmission network scheme is shown in Fig. 5 [12]–[15].

The largest electrical energy producers in Riga are two CHP or cogeneration plants Riga CHP-1 and Riga CHP-2, as well as Riga HPP of JSC Latvenergo. Additional electrical energy is provided by independent cogeneration power plant Imanta CHP, operated by JSC Rigas Siltums, and by other small cogeneration power plants, whose impact on the whole power adequacy of Riga city is insignificant. All the above-mentioned power plants are connected to the transmission power network. The largest electrical energy producers (Name of power plant – Installed capacity in MW – Fuel) are as follows: Riga CHP-1, 144, natural gas; Riga CHP-2, 880, natural gas; Riga HPP, 402, water; Imanta CHP, 48, natural gas [12], [15], [19], [21].

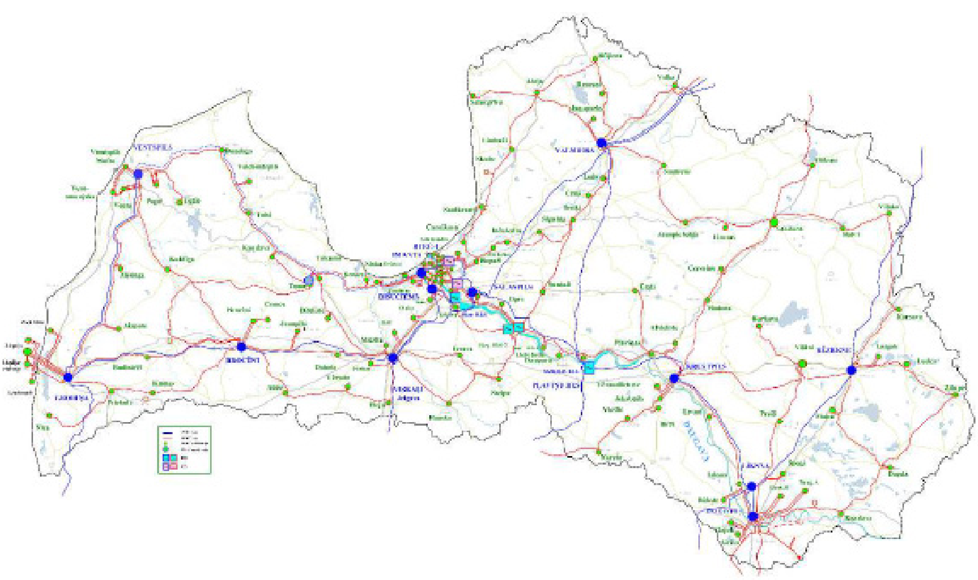

*Fig. 5.* 330 kV and 110 kV power transmission network scheme in Latvia.

## 3. CRITICAL INFRASTRUCTURE

Upon examining the natural gas supply system of Latvia, it can be seen that seven critical points can be determined, which may influence natural gas supply reliability [3], [13], [16], [17], [22]–[24].

1. KIEMENAI gas metering station. The station is situated in the territory of the Republic of Lithuania. The transmission system operators of both countries, JSC Conexus Baltic Grid and JSC Amber Grid (Lithuania) have signed a contract regarding the use of the measurements made at the gas-metering station in the metering of gas transported across borders and the measurement of its quality. The requirements regarding the quality of natural gas are laid down in Latvian State Standard LVS 459 "Natural Gas. Properties, Parameters, Quality Assessment of Gas" (Latvian State Standard LVS459). The capacity of the station is 6.48 million m $m^3$/day. The gas-metering station ensures the transport of natural gas from Lithuania to Latvia and Estonia, as well as from Estonia, and Latvia to Lithuania. Power supply of gas metering station is provided from substation "Bauska" through two 110 kV transmission lines and respectively trough the 20 kV network. Reservation of power supply can be implemented through 20 kV network, and additional autonomous diesel generators are installed in the gas metering station.
2. KARKSI gas metering station. The station is situated in the territory of the Republic of Estonia. The transmission system operators of both countries, JSC Conexus Baltic Grid and JSC Elering (Estonia) have signed a contract regarding the use of the measurements made at the gas-metering station in the metering of gas transported across borders and the measurement of its quality (Latvian State Standard LVS459). The capacity of the station is 6.96 million billion $m^3$ /day. The station ensures the transport of natural gas from Latvia to Estonia and from Estonia to Latvia. Power supply of gas metering station is provided in Estonia. Reservation of power supply can be implemented from Latvia through 20 kV network, and additional autonomous diesel generators are installed in the gas metering station.
3. KORNETI gas metering station. The station is situated in the territory of the Republic of Latvia. The station meters the gas and measures its quality. The transmission system operators of both countries, JSC Conexus Baltic Grid and JSC Gazprom (Russia) have signed a contract regarding the use of the measurements made at the gas-metering station in the metering of gas transported across borders and the measurement of its quality. The requirements regarding the quality of natural gas are laid down in Latvian State Standard LVS 459. The capacity of the station is 20 million billion $m^3$ /day. This capacity makes it possible to transport natural gas via the transmission system of JSC Conexus Baltic Grid to Incukalns underground gas storage as well as to Lithuania and Estonia. Power supply of gas metering station is provided through 20 kV network. Reservation of power supply can be implemented through 20 kV network, and additional autonomous diesel generators are installed in the gas metering station.
4. Incukalns underground gas storage. Incukalns UGS ensures pumping-in of gas in the summer period and pumping-out of gas in the winter period. The amount of gas that can be stored is 4.5 billion $m^3$ (active gas 2.3 billion $m^3$). The pumping-in

capacity in the summer season is 17 million m3/day and the maximum pumping-out capacity is 28 million billion $m^3$ /day. Incukalns underground gas storage is the only gas storage in the Baltic region. Incukalns UGS ensures the storage of a safety reserve of natural gas for the whole region. This UGS is equipped with a metering unit, which ensures the metering and quality monitoring of the gas pumped in and out in compliance with Latvian State Standard LVS 459. Power supply of IUGS is provided from substation "Incukalns" through two 110 kV transmission lines and, respectively, thought the 20 kV network. Reservation of power supply can be implemented through 20 kV network, and additional autonomous diesel generators are installed in the IUGS.

5. RIGA 1 gas regulation station. Gas-regulating station Riga 1 ensures the supply of natural gas to Riga CHP-1 of JSC "Latvenergo". The capacity of the station is 175 thousand billion $m^3$ /h. Gas-regulating station Riga 1 ensures gas metering and quality measurements in compliance with Latvian State Standard LVS 459. The location of metering stations at these facilities will ensure gas quality assessment for the following consumers: the obtained data will be used for billing the consumers of the right bank of the Daugava in Riga; the data will also be sent to GRS Riga 3, which supplies gas to Riga CHP-2. Power supply of GRS Riga 1 is provided from 330 kV substation "Riga CHP-1" network through 110 kV trans-mission lines and respectively the 20 kV network. Reservation of power supply can be realised through 20 kV network and additional autonomous diesel generators are installed in the GRS. Primary equipment of CHP-1 was commissioned in 2005, excluding heat only boiler (HOB) No. 3 which started its operation in 2010. Generating equipment of CHP-1 consists of combined cycle gas turbine (CCGT) double unit with installed heat capacity of 145 MWth and electric capacity of 144 MWel as well as three heats only boilers with heat capacity of 348 MWth. Thus, total installed heat capacity of CHP-1 is 493 MWth and electric capacity is 145 MWth. The main fuel for CCGT unit and HOBs is natural gas while light oil (diesel) is used as the emergency fuel for heat only and auxiliary boilers.
6. RIGA 3 gas regulation station. Gas-regulating station Riga 3 ensures the supply of natural gas to Riga CHP-2 of JSC Latvenergo. The capacity of the station is 300 thousand billion $m^3$/h. Gas-regulating station Riga 3 ensures gas metering and quality measurements in compliance with Latvian State Standard LVS 459. Power supply of GRS Riga 3 is provided from 330 kV substation "Riga CHP-2" network through 110 kV transmission lines and, respectively, the 20 kV network. Reservation of power supply can be implemented through 20 kV network, and additional autonomous diesel generators are installed in the GRS.

Primary equipment of CHP-2 was commissioned during the period from 1973 to 2013. CCGT unit No.1 and its auxiliary systems started its operation in 2008, while CCGT unit No.2 and its auxiliary systems were launched in 2013. CHP-2 heat only boilers HOB-1, 2, 3 and 4, originally built from 1973 to 1993, were reconstructed during 2009–2011. Installation of low NOx burners allowed reducing NOx emissions. Heat only boiler No. 5 was put in operation in 2013. Installed electric capacity of CCGT unit No. 1 is 413 MWel in cogeneration mode and 442 MWel in condensing mode, while installed heat capacity is 274 MWth.

Output of CCGT unit No. 2 is slightly different: installed electric capacity in cogeneration mode is 419 MWel, in condensing mode 439 MWel, heat capacity is 270 MWth. Total heat capacity of five heat only boilers HOB-1, 2, 3, 4, 5 is 580 MWth. Considering the whole plant, CHP-2 installed capacity in cogeneration mode is 832 MWel, in condensing mode 881 MWel and overall heat capacity is 1124 MWth. Similarly to CHP 1, natural gas is used as the main fuel and diesel is used as the emergency fuel for CHP-2.

7. ZIEMELI gas regulation station. The station ensures the supply of natural gas to the city of Riga and to the western part of the Republic of Latvia, including national-status cities: Jelgava, Jurmala, and Liepaja. The capacity of the station is 150 thousand billion $m^3$ /h. The gas-regulating station ensures gas metering and quality measurements in compliance with Latvian State Standard LVS 459. The location of metering stations at these facilities will ensure gas quality assessment for consumers in the following locations: Riga left bank, Balozi, Kekava, Iecava, Code, Bauska, and Uzvara. The data obtained at GRS Ziemeli will also be used at the gas-regulating stations of the villages of Baldone and Daugmale. Power supply of gas metering station is provided from substation "Iecava" through two 110 kV transmission lines and, respectively, through the 20 kV network. Reservation of power supply can be implemented through 20 kV network, and additional autonomous diesel generators are installed in the gas metering station [6], [7], [11], [14], [22].

## 4. INCREASING THE RELIABILITY OF THE REGIONAL NATURAL GAS SYSTEM

The existing scheme of gas supply is in proper order and duly ensures the required capacities. To increase the reliability of the regional gas supply system, the following should or can be done:

- The capacities of the intercountry connections have to be increased: reconstruction of the border-area GMS Karksi and Kiemenai to increase the flow rate; construction of a reverse unit at GMS Karksi;
- A new transmission pipeline can be built to replace the Riga–Vilnius pipeline that has been allocated for the needs of the distribution system;
- A connection between the pipelines Riga–Daugavpils and Vilnius–Visaginas can be made (40 km, DN 400);
- A connection between the pipelines Iecava–Liepaja and Panevezys–Klaipeda can be made (95 km, DN 400);
- The overall capacity and the gas pumping-out capacity of Incukalns UGS has to be increased;
- Additional compressors at Incukalns UGS can increase the amounts pumped in and ensure compressed pumping-out;
- In order to plan and be able to switch over gas flows, a regional SCADA system is needed with dynamic software of hydraulic calculations linked to it [3], [5], [6], [18], [21], [23], [24].

## 5. SWOT ANALYSIS

Strengths:

- A high natural gas reliability level with a natural gas infrastructure reserve of 45 %;
- A technologically optimal high-pressure natural gas transmission infrastructure in Latvia, especially in territories with a higher level of economic activity;
- A good technical condition of the natural gas transmission and distribution pipelines, modernized and reconstructed gas-metering stations;
- Natural gas supply in the winter period is ensured by Incukalns UGS, which also serves as a pledge of security all year round;
- An environment-friendly source of energy characterised by a low level of CO2 emissions and an efficient fuel with a high calorific value.

Weaknesses:

- Too few interconnections with other EU member states;
- The insufficient capacity of the Latvia–Lithuania interconnection.

Opportunities:

- Diversification of the natural gas supply paths, building new transmission system connections, and construction of a competitive LNG terminal;
- Supply of natural gas from Klaipeda LNG terminal;
- Setting up a Baltic natural gas trade platform/centre, with the participation of Latvia;
- If the natural gas consumption in the region increases in the long-term development of other potential natural gas storage sites, it allows for storage of natural gas for the markets of other EU countries;
- Increasing the natural gas storage potential at Incukalns UGS using the non-domestic storage potential;
- Development of the production of biogas, gas produced from wood biomass and EtO gas; introduction of these gases into the natural gas distribution system;
- Ample possibilities of using natural gas both in industrial equipment and in heat supply equipment, especially combined heat and power generation equipment with high energy efficiency, simultaneously generating heat and electric power;
- Using natural gas in the transport sector if gas-filling infrastructure is ensured.

Threats:

- The possible increase in the natural gas price on the global market;
- Diminished natural gas consumption may increase the costs of using the gas infrastructure to the gas users;
- Supply interruptions during the period when gas is pumped into Incukalns UGS;

- Insufficient gas supply in the period of high consumption (in the winter season) in case of accidents in the Baltic natural gas systems;
- Control of strategically important gas supply and storage infrastructure;
- As the natural gas consumption increases, Latvia's energy independence weakens.

Challenges:

- Lack of interconnections with other EU countries, which hampers the development of the underground gas storage potential in Latvia;
- Insufficiently diversified natural gas supply sources and paths, leading to a strong dependence on one supplying country. As the natural gas supply paths develop in Estonia and Finland, reverse gas flow – from Estonia to Latvia there will be no reverse gas flow;
- Insufficient capacity of the Latvia–Lithuania interconnection for meeting the Latvian gas demand in the case when the gas demand is extremely high and the supply of gas from Incukalns UGS is interrupted;
- For regional security needs, it would be important to enlarge Incukalns UGS [3], [8], [9].

## 6. CONCLUSIONS

The main critical points of the system have been determined within the framework of the research. First of all, these include the border-area GMSs, with a total capacity of 23 million $m^3$/day, for example GMS Korneti (in the territory of Latvia) – 17 million $m^3$/day and GMS Kiemenai (in the territory of Lithuania). The present capacity of GMS Kiemenai is 6.24 million $m^3$/day, still after the reconstruction of the station; it will be possible to increase it to 10 million billion $m^3$ /day. Border-area GMS Karksi (in the territory of Estonia), which has a gas-metering capacity of 7 million billion $m^3$ /day, operates only in the direction towards Estonia and is mainly used in winter, during the heating season. In order to ensure the possibility to transport gas from Estonia to Latvia, this GMS needs to be equipped with a reverse metering unit.

In the territory of Latvia, there are 44 GRS. As a result of the study, three GRS have been chosen as critical points (Riga 1, Riga 3 and Ziemeli) since they serve the largest natural gas consumer in Latvia – the city of Riga with adjoining gasified areas. According to the 2015 report data, the total consumption in Riga makes up 73 % of the country's total consumption. These GRS also supply gas to energy facilities: Riga CHP-1 and 2 as well as facilities of JSC Rigas Siltums.

Incukalns UGS has also been ranked among the most critical point of the system. This is due to the fact that in the winter season, as the demand of natural gas for heat generation needs increases, the capacity of the pipelines is not sufficient to meet the natural gas demand of the whole Baltic region. Therefore, in winter, during the heating season, the gas stored in Incukalns UGS is used, which is supplied from the UGS to the consumers of Latvia and, partly, Estonia. In the summer season, when gas is pumped into Incukalns UGS, in an average daily amount of 16 million billion $m^3$ /day, reaching 17 million billion $m^3$ /day on some days.

Considering the permissible working pressure of the gas pipeline Valday–

Pskov–Riga (44...47 bar), such an amount corresponds to the maximum capacity of the pipeline, serving an average gas demand of 2...2.2 million m$^3$/day in Latvia as well as pumping of gas into Incukalns UGS. At the same time, Incukalns UGS needs to be enlarged and modernized.

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## LATVIJAS GĀZES – ELEKTROENERĢIJAS TĪKLS: GĀZES SISTĒMAS DATU ANALĪZE

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### K o p s a v i l k u m s

AS “Conexus Baltic Grid” ir vienotais dabasgāzes pārvades un glabāšanas operators Latvijā. Tas nodrošina Inčukalna pazemes gāzes krātuves (PGK), gāzesvadu cauruļvadu sistēmā ar kopējo garumu 1191 km gāzes skaitītāju stacijas Korneti darbību. Latvijas dabasgāzes pārvades infrastruktūra ir daļa no Baltijas valstu dabasgāzes pārvades sistēmas. Inčukalna PGK ir viens no svarīgākajiem dabasgāzes infrastruktūras elementiem. Tas spēj uzglabāt līdz 2,32 miljardiem $m^3$ aktīvās gāzes un ļauj samazināt pieprasījuma svārstības Baltijas valstīs. Ziemas periodā patērētāji Latvijā saņem dabasgāzi no Inčukalna PGK. No tās dabasgāze tiek piegādāta arī patērētājiem Igaunijā un laiku pa laikam Lietuvā. Vasaras sezonā krātuvē vidēji diennaktī iesūknē 16 miljoni $m^3$ gāzes Ņemot vērā pieļaujamo darba spiedienu, šāds daudzums atbilst cauruļvada maksimālajai jaudai, nodrošinot vidējo gāzes pieprasījumu Latvijā 2-2,2 miljonu $m^3$ diennaktī. Šajā pētījumā tika noteikta dabasgāzes kritiskā infrastruktūra, gāzes pieprasījums un piegāde, kā arī tika veikta šīs sistēmas SVID analīze.

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# THE EFFECT OF FUEL QUALITY ON CARBON DIOXIDE AND NITROGEN OXIDE EMISSIONS, WHILE BURNING BIOMASS AND RDF

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The article analyses the variations in carbon dioxide emission factor depending on parameters characterising biomass and RDF (refuse-derived fuel). The influence of moisture, ash content, heat of combustion, carbon and nitrogen content on the amount of emission factors has been reviewed, by determining their average values. The options for the improvement of the fuel to result in reduced emissions of carbon dioxide and nitrogen oxide have been analysed. Systematic measurements of biomass parameters have been performed, by determining their average values, seasonal limits of variations in these parameters and their mutual relations. Typical average values of RDF parameters and limits of variations have been determined.

***Keywords:*** *ash content, biomass, carbon content, carbon dioxide, emissions, heat of combustion, moisture, nitrogen oxides, refuse-derived fuel*

## 1. INTRODUCTION

Biomass is a renewable energy source with considerable potential in replacing fossil fuel. As the interest in biomass as a renewable and carbon dioxide ($CO^2$) neutral energy source is growing, the interest in the influence of biomass combustion on the environmental pollution, climate and climate change is growing as well [1]–[4]. Biomass combustion results in the emissions of gaseous and solid particles in the atmosphere, for instance, carbon dioxide, methane and nitrogen oxides, which create the greenhouse effect and are hazardous for the environment and human health [2], [3]. Most commonly used biomass includes various types of wood of coniferous and deciduous trees – branches, leaves, bark, forestry waste, tree, shrub and wood residues, sawdust and bark from felling sites, which are also referred to as wood waste and wood chips, granules, and briquettes. It has been experimentally proven [5], [6], [7] that the nitrogen contained in the biomass during combustion is the principal source of NOx emissions, namely, as the content of nitrogen increases in fuel, the amount of nitrogen oxide emissions increases proportionately. The other three mechanisms of nitrogen oxide generation that result in nitrogen oxide emissions are not that significant, since they are associated with relatively high temperatures of more than 1,200 °C, while the typical temperature in biomass combustion furnaces does not exceed 1,100 °C. The content of nitrogen in the wood is pre-determined by several factors: type of wood or the composition of fuel, environment, where the trees have grown – climate, soil, degree of pollution, external pollution during the preparation of fuel, age of the wood, etc. All of these factors determine the content of carbon and nitrogen in the biomass and the resulting $CO_2$ and NOx emissions, as the biomass is burnt.

One of the most significant alternatives to fossil energy sources and renewable energy sources alike is refuse-derived fuel (RDF). There are two types of RDF – sorted material or refuse-derived fuel from non-hazardous waste and solid recovered fuel (SRF). In accordance with the standard LVS EN 15359:2012 "Solid Recovered Fuel Specifications and Classes", the solid recovered fuel has been divided into five classes, depending on its parameters. Biomass can be, to some extent, classified as RDF, however, the characterising parameters of this type of fuel and, consequently, possible emissions differ, because the lowest heat of combustion, as well as carbon and nitrogen content of these materials are different. RDF that is suitable for certain use (predominantly, the production of concrete) is currently used in relatively low quantities in Latvia.

## 2. MEASURING EQUIPMENT AND MEANS

When taking measurements for determining the carbon content in fuel and the corresponding GHG emission capacity in flue gases, the following equipment was used:

- Element analyser "*Flash EA1112 Series*", company "*Thermo Fisher Scientific*", Holland.
- Gas analyser "*SWG*-200-1", *MRU GmbH*, Germany.
- Calorimeter "*Berthelot Mahler*", company "*I.S.Co.*", Italy; with additional equipment.
- Calibrated containers for determining the density of the fuel material.
- For calibration, benzoic acid $C_6H_5COOH$, dodecane $C_{12}H_{26}$, acetanilide $C_8H_9NO$ and atropine $C_{17}H_{23}NO_3$ of the corresponding quality were used.

## 3. MEASUREMENT METHODOLOGY

For determining carbon content in fuel, CHN analyser was used in accordance with the Standard LVS EN ISO 16948; for determining calorific values – LVS EN ISO 18125; for determining moisture – LVS EN ISO 18134; for determining the amount of ashes – LVS EN ISO 18122 and for determining bulk density – LVS EN ISO 17828. For recalculating the data of the analysis for various bases, the standard LVS EN 15296 was used. In CHN analysers, a very small amount of the material was used as a sample – by weighing it very precisely, in milligrams, before inserting it into the unit. To avoid the systematic error, analyser was additionally calibrated by using a stable, lightly volatile and strongly defined chemical. For calibration, benzoic acid $C_6H_5COOH$, dodecane $C_{12}H_{26}$, acetanilide $C_8H_9NO$ and atropine $C_{17}H_{23}NO_3$ of the corresponding quality were used.

*3.1. Sampling*

Laboratory data of the biomass fuel parameters, during the second half of 2016 and January–May 2017, acquired from Latvian companies, were gathered. This way we could collect an excellent and representative range of wood fuel samples, for which the deviation of parameters could be wide. The samples were prepared for the analysis in accordance with the requirements that were set forth for measuring the specific parameters, according to the aforementioned standards.

*3.2. Deviation and Representation of Parameters*

The deviation of parameters for biomass is well represented in Fig. 1, where all the data of the wood pellet analysis conducted in the laboratory, during the four months in 2017 and the entire year of 2016, were gathered. Figure 1 shows the dependence of the net calorific value on moisture. It can be split into two groups – pellets with an ash content of up to 0.5 % (blue squares), and pellets with an ash content above 0.5 % (pink circles). In accordance with the standard LVS EN ISO 17225-2, wood pellet is divided into specification classes A1, A2, and B. Two groups (sets) of the pellet are formed to ensure that one of the two sets belongs to the class A1 according to ash content, e.g., ash content does not exceed 0.5 %. In Fig. 1, each of the mentioned sets is approximated with a straight line. In the ideal situation – if the calorific value depended only on humidity, all experimental points would form such a straight line. In fact, it is a set where each measurement is equivalent to others.

Both sets often overlap, which is why, when determining the average $Q_{net}$ value, all the values in the range 16.8–18.4 GJ/t were taken into account. In this case, more than 300 samples were analysed.

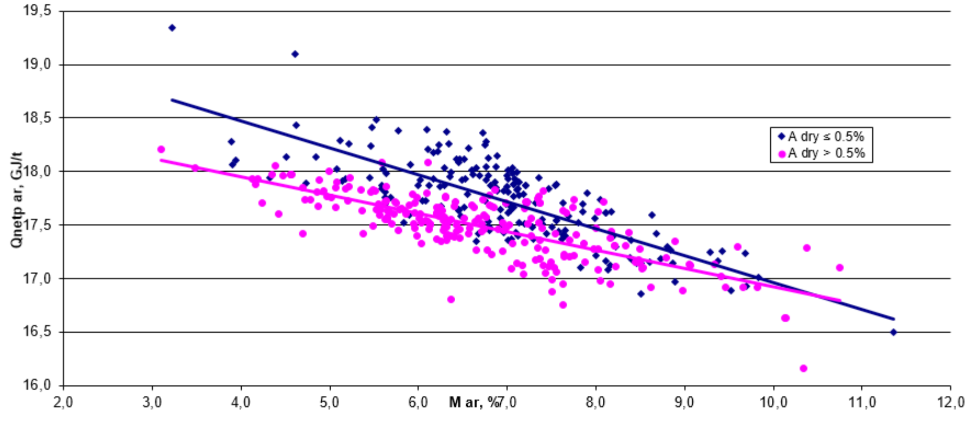


*Fig.* 1. The dependence of moisture content on the calorific values for different wood pellet samples.

It is obvious that seasonality impact on this scattering is very low. Only in 2.5 % of cases, humidity is out of the interval 4–10 % and does not depend on seasonality. It is understandable because pellet production technology does not depend on the season and weather circumstances.

In Fig. 2, scattering of the chips and wood residue parameters is given. Explanation of the scattering is the same as for Fig. 1 (see above); only in this case scattering is much larger. This can be explained with physical and chemical as well as humidity differences in examples.

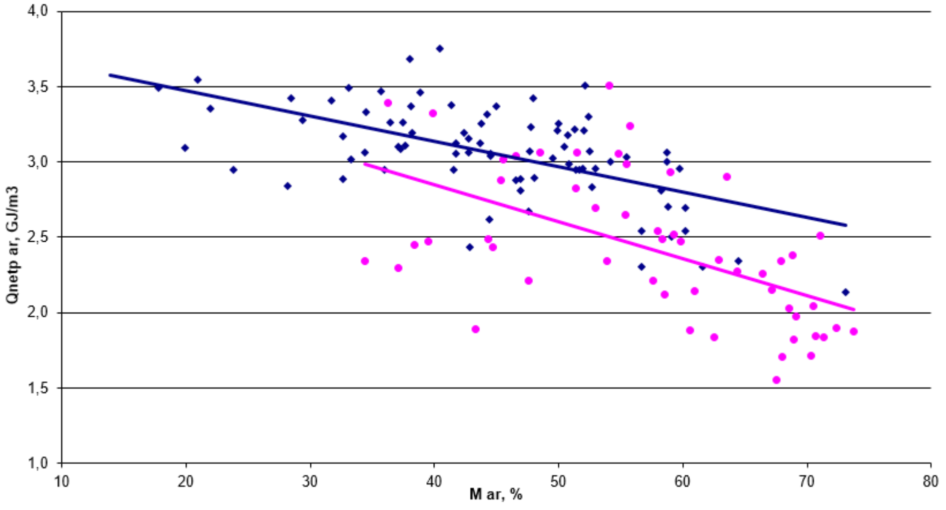


*Fig. 2.* The dependence of net calorific value of the wood chips and timber offcuts and residues on moisture. Note: "pink circles" – residues; "blue squares" – chips.

*3.3. Seasonality*

The seasonal changes in the wood fuel material parameters may be mainly related to the change in the moisture content. However, the analysis revealed that wood pellet and briquette seasonality was almost unnoticeable. It is understood that at a greater extent the moisture content depends on the technological production process of the fuel. Dependence on seasonality of the humidity of wood chips and wood residues is noticeable but not significant.

*3.4 Calculation of Emission Factors*

The $CO_2$ emission factor was calculated by taking into account the physicochemical characteristics experimentally determined during the research, by using the emission factor calculation formula (1). Oxidation factor p according to the IPCC Guidelines is determined p = 1.

$$E'_{CO2} = \frac{C^d \times M_{CO_2} \times 1000}{Q_z^d \times M_C \times 100}, \quad (1)$$

where $E'_{CO2}$ – $CO_2$ emission factor (t $CO_2$/TJ);
$C_d$ – coal content in fuel operating weight (%);
$M_{CO2}$ – $CO_2$ molecular weight (44.0098 g/mcl);
$M_C$ – C molecular weight (12.011 g/mcl);
$Q_z^d$ – net calorific value of fuel operating weight (GJ/t);
1000 – transition from GJ to TJ;
100 – determining % value.

## 4. RESULTS

The average values of parameters in $CO_2$ and NOx emissions by fuel combustion are collected in Table 1.

*Table 1*

**The Average Values of Parameters in $CO_2$ and NOx Emissions by Fuel Combustion**

| Fuel | Moisture, % | $Q_{net}$ value | Carbon content, % | Nitrogen content, % |
|---|---|---|---|---|
| Firewood | Average 51 | 7.73 GJ/bulk.m$^3$ | 22.88 | 0.06 |
| | 10 | 16.24 | 42.03 | 0.11 |
| | 20 | 14.16 | 37.36 | 0.10 |
| | 30 | 12.09 | 32.69 | 0.08 |
| | 40 | 10.01 | 28.02 | 0.07 |
| | 55 | 6.9 | 21.02 | 0.05 |
| Wood residue [1] | Average 57.2 | 2.69 GJ/bulk.m$^3$ | 20.3 | 0.43 |
| Wood chips [2] | Average 44.7 | 3.26 GJ/bulk.m$^3$ | 23.92 | 0.25 |
| Wood briquettes | Average 9.65 | 16.78 GJ/t | 48.1 | 0.11 |
| Wood pellets | Average 7.38 | 17.54 GJ/t | 49.83 | 0.11 |
| RDF; SRF | Average 10.3 | 20.8 GJ/t | 51.42 | 0.93 |

Note: [1] Bulk density for residue 0.424 kg/m$^3$

[2] Bulk density for chips 0.367 kg/m$^3$

### *4.1. SRF and RDF Characterisation*

According to the stipulations of the EN 15359 [8], solid recovered fuel is defined as quality assured fuel, and it should not be confused with the RDF. RDF is a non-standardised low quality fuel that contains mixed unprocessed combustible components of municipal solid waste and uses only energy from waste plants [9]. According to Wilén *et.al.* [10], the high quality recovered fuels (class SRF I) can be produced from commercial, construction, demolition and industrial waste, but quality class SRF II-III from household and commercial waste after source separation. According to [11], the coarse fraction after mechanical pre-treatment of municipal solid waste is suitable for the production of refuse derived fuel in Latvia.

A lower heating value of RDF is 12–16 MJ/kg, moisture 15–25 % and ash 10–22 % [12]. According to Nithikul [13], a lower heating value (LHV) of RDF is 19.4 MJ/kg and percent of C is approximately 57 % in Thailand.

The average theoretical LHV of RDF is calculated as 15.7 MJ/kg, but the experimentally determined LHV of RDF samples was 15.1 MJ/kg, ash content was 16 % and moisture content was 6 % in Latvia [14]. The elemental analysis for solid recovered fuels is C – 47.1 % (dry basis), H – 7.1 %, O – 29.4 %, N – 0.7 %, S – 0.24 %, Cl – 0.6 % [15]. According to Conesa *et al*. [16], the elemental and proximate analyses of SRF are C – 40.85 % (wt. %), H – 5.33 %, O – 42.39 %, N – 1.07 %, S – 0.15 %, and humidity – 16.7 %. According to Kim *et al.* [17], the elemental analysis of SRF showed that 66.8–70.39 % of the samples comprised carbon, 16.81–18.81 % comprised hydrogen, 11.19–15.47 % accounted for oxygen, and only 1% was nitrogen and sulphur. The present results for RDF and SRF parameter measurements in Latvia are collected in Table 2.

*Table 2*

**Parameters of RDF and SRF in Latvia**

| | $W_{ar}$ | $A_{dry}$ | $Q_{gr}$ | $Q_{gr}$, dry | $Q_{netp}$, AR | S, dry | Cl, dry | N, dry | C, dry | H, dry | DT | FT |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **No.** | % | % | MJ/kg | MJ/kg | GJ/t | % | % | % | % | % | °C | °C |
| **1** | 2.8 | 51.5 | 12.72 | 13.08 | 11.34 | 0.57 | 0.85 | 1.45 | 33.15 | 3.77 | - | - |
| **2** | 1.6 | 29.4 | 26.05 | 26.47 | 24.68 | 0.29 | 1.18 | 0.69 | 53.75 | 6.02 | - | - |
| **3** | 2.3 | 31.5 | 26.33 | 26.96 | 24.95 | 0.29 | 1.77 | 0.81 | 55.22 | 5.89 | 1120 | 1190 |
| **4** | 2.0 | 29.5 | 24.06 | 24.54 | 22.69 | 0.30 | 1.72 | 1.25 | 43.31 | 3.84 | - | - |
| **5** | 2.2 | 18.6 | 24.67 | 25.21 | 23.30 | 0.30 | 1.78 | 1.29 | 50.52 | 5.39 | - | - |
| **6** | 2.9 | 13.7 | 23.69 | 24.40 | 22.31 | 0.26 | 1.12 | 0.89 | 58.65 | 7.11 | 1160 | 1210 |
| **7** | 2.2 | 17.0 | 22.78 | 23.30 | 21.41 | 0.28 | 1.58 | 0.59 | 55.74 | 7.34 | 1120 | 1200 |
| **8** | 1.8 | 41.7 | 22.85 | 23.26 | 21.48 | 0.52 | 1.84 | 0.67 | 43.55 | 6.31 | - | - |
| **9** | 2.5 | 19.5 | 22.49 | 23.07 | 21.12 | 0.41 | 1.09 | 0.80 | 49.04 | 7.04 | - | - |
| **10** | 2.1 | 16.6 | 26.47 | 27.04 | 25.10 | 0.33 | 1.16 | 0.66 | 61.03 | 9.22 | 1130 | 1220 |
| **11** | 3.7 | 15.5 | 20.95 | 21.75 | 19.56 | 0.24 | 1.28 | 1.28 | 49.29 | 6.87 | - | - |
| **12** | 26.5 | 12.8 | 24.69 | 33.61 | 23.05 | 0.23 | 2.22 | 0.34 | 59.00 | 7.80 | 1150 | 1200 |
| **13** | 22.4 | 9.5 | 26.94 | 34.72 | 25.34 | 0.19 | 2.18 | 0.35 | 61.00 | 8.20 | 1150 | 1200 |
| **14** | 31.1 | 19.1 | 16.36 | 23.74 | 14.67 | 0.30 | 1.28 | 1.56 | 52.97 | 6.28 | 1150 | 1240 |
| **15** | 40.4 | 16.2 | 11.29 | 18.94 | 9.50 | 1.02 | 2.88 | 1.32 | 45.03 | 6.21 | 1130 | 1210 |
| **16** | 24.6 | 15.1 | 19.28 | 25.58 | 17.66 | - | - | - | - | - | 1140 | 1230 |
| **17** | 7.5 | - | 28.91 | 31.26 | 27.47 | - | 0.81 | - | - | - | - | - |
| **18** | 14.0 | - | 19.74 | 22.96 | 18.24 | - | 1.13 | - | - | - | - | - |
| **19** | 3.6 | - | 22.79 | 23.63 | 21.40 | - | 0.42 | - | - | - | - | - |
| **Ave-rage** | 10.3 | 22.3 | 22.27 | 24.92 | 20.80 | 0.37 | 1.46 | 0.93 | 51.4 | 6.49 | 1139 | 1208 |
| **St. dev.** | 12.3 | 11.5 | 4.69 | 4.86 | 4.76 | 0.21 | 0.59 | 0.40 | 7.78 | 1.46 | - | - |
| **Min** | 1.6 | 9.5 | 11.29 | 13.08 | 9.50 | 0.19 | 0.42 | 0.34 | 33.2 | 3.77 | - | - |
| **Max** | 40.4 | 51.5 | 28.91 | 34.72 | 27.47 | 1.02 | 2.88 | 1.56 | 61 | 9.22 | - | - |

We can see that the value of the parameters vary in the very broad range and all depends on collection and separation technology. Minimising moisture content in raw materials is of significance for production of good quality SRF.

## 5. EMISSION FACTORS

$CO_2$ and NOx emission factors are collected in Table 3.

*Table 3*

**$CO_2$ and NOx Emission Factors**

| Fuel | Fuel carbon consump-tion (C), % | Net calorific value ($Q_z$), GJ/t | Emission factors ($E'_{CO2}$), t/TJ | Nitrogen consump-tion (N) % | Nitrogen oxides emission factors ($E'_{NO2}$),t/TJ |
|---|---|---|---|---|---|
| Firewood, W=51% (Latvia average) | 22.88 | 7.73 | 108.45 | 0.06 | 0.2844 |
| Firewood, W=20% | 37.36 | 14.16 | 96.67 | 0.10 | 0.2587 |
| Firewood, W=40% | 28.02 | 10.01 | 102.57 | 0.07 | 0.2562 |
| Wood residue W=57.2% | 20.3 | 2.69 | 117.32 | 0.43 | 2.4851 |
| Wood chips, W=44.7% | 23.92 | 3.26 | 98.703 | 0.25 | 1.0316 |
| Wood briquettes, W=9.65% | 48.1 | 16.78 | 105.03 | 0.11 | 0.2402 |
| Wood pellets, W=7.38% | 49.83 | 17.54 | 104.09 | 0.11 | 0.2298 |
| RDF W= 10.3% | 51.42 | 20.8 | 90.58 | 0.93 | 0.6383 |

## 6. MEASUREMENT UNCERTAINTY

Measurement uncertainty, when determining the specific parameter, was performed in accordance with the Theory of Errors. The standard deviation of each parameter was determined 10 times by measuring the same sample and by determining the average deviation, which described the deviation in the acquired result. In CHN measurements, the uncertainty estimation was included in the software of the device. The absolute result was recalculated to the relative error: carbon content uncertainty was ±1.5%; moisture ±2.0%; ash amount ±2.5%; calorific value ±4.5%; density ±5%.

For wood materials, the EF uncertainty estimation was significantly larger, because the parameter variations were much larger and by using the IPCC methodology the uncertainty increased. The estimated EF determination errors for wood materials are reflected in Table 4.

*Table 4*

**The Uncertainty of Determining Emission Factors**

| Fuel | Uncertainty, ± % |
|---|---|
| Diesel fuel | 2 |
| Coal | 3 |
| Firewood | 5 |
| Pellets and briquettes | 4 |
| Wood chips and timber offcuts | 10 |

## 7. CONCLUSIONS

1. The research of Latvian wood biomass and RDF parameters has been performed. The variations in carbon dioxide and nitrogen oxide emission factor depending on parameters characterising biomass and RDF have also been analysed.
2. The influence of moisture, ash content, heat of combustion, carbon and nitrogen content on the amount of emission factors has been reviewed by determining potential limits of their variations for each type of fuel.
3. The options for the improvement of fuel have been offered, thus ensuring lower emissions of carbon dioxide and nitrogen oxides; in the event of biomass they include the reduction of moisture and ash content, for RDF – more thorough sorting of raw materials.
4. The average values of RDF parameters and limits of their variations have been determined; the values of $CO_2$ and NOx emission factors of biomass and RDF have been compared and analysed.

## *ACKNOWLEDGEMENTS*

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## KURINĀMĀ KVALITĀTES IETEKME UZ OGLEKĻA DIOKSĪDA UN SLĀPEKĻA OKSĪDU EMISIJĀM, SADEDZINOT BIOMASU UN NAIK

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### K o p s a v i l k u m s

Rakstā analizētas oglekļa dioksīda un slāpekļa oksīdu emisijas faktora izmaiņas atkarībā no biomasu un NAIK (no atkritumiem iegūtais kurināmais) raksturojošiem parametriem. Apskatīta mitruma, pelnu satura, sadegšanas siltuma oglekļa un slāpekļa satura ietekme uz emisijas faktoru lielumu, nosakot to vidējās vērtības. Analizētas kurināmā materiāla uzlabošanas iespējas, nodrošinot mazākas oglekļa dioksīda un slāpekļa oksīdu emisijas. Veikti sistemātiski biomasas parametru mērījumi, nosakot vidējos lielumus, sezonālas parametru izmaiņu robežas, un savstarpējās attiecības. Noteiktas tipiskas NAIK parametru vidējās vērtības un izmaiņu robežas.

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# SUSTAINABLE CONSTRUCTION INDUSTRY DEVELOPMENT AND GREEN BUILDINGS: A CASE OF LATVIA

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Nowadays, more and more attention is being paid to the country's economy, construction industry and real estate market's sustainable development and to the studies related to these issues. The aim of the research is to analyse significant aspects of sustainable development of construction activities and real estate market, with particular focus on environmental aspects of construction or the role of green buildings. The research includes an integrated approach of construction industry analysis and analysis of real estate operations area. Scientific and practical solutions and recommendations will enable the industry participants to be introduced to the main sustainable aspects of construction industry development, which, in their turn, can improve the overall performance of the industry in the long term.

***Keywords:*** *construction, energy efficiency, environment, sustainable real estate market development.*

## 1. INTRODUCTION

The research is continuation of previous studies, such as Kauškale et al. (2017) [4], Kauškale et al. (2016) [3] and Kauškale, Riemenschneider (2017) [5]. The aim of the research is to analyse significant aspects of sustainable development of construction activities and real estate market, with particular focus on environmental aspects of construction and a role of green buildings.

Research methods include a combination of quantitative and qualitative research methods, such as analysis, synthesis, statistical data processing, logical assess, comparison method, qualitative data collection, questionnaire and other methods. The survey is focused on Construction and Real Estate Operations of the national economy sectors – such as managers and employees of enterprises who are working in development of building projects, construction of residential and non-residential buildings, civil engineering, real estate agencies, management of real estate on a fee or contract basis, renting and operating of own or leased real estate, buying and selling of own real estate. The research includes an integrated approach of construction industry analysis and analysis of real estate operations area.

Scientific and practical solutions and recommendations will enable the industry participants to be introduced to the main sustainable aspects of real estate market and construction activities, which, in their turn, can improve the overall performance of the industry in the long term.

## 2. OVERVIEW OF THEORETICAL ASPECTS AND RESEARCH METHODOLOGY

Sustainable development of construction industry and real estate market requires a complex approach. Houses, which are constructed in accordance with the principles of sustainable construction, have the following characteristics [7, pp. 139–140]:

- high energy efficiency (low-energy buildings) with the annual heat energy consumption of less than 50 kWh/m2, for normal projects with 150–200 kWh/m2;
- passive houses, geographical location, high thermal heat insulation materials, green energy acquisition sources are used in the construction process. Annual energy consumption for these projects amounts to 15 kWh/m2;
- particularly energy-efficient (zero-energy) buildings are using only alternative energy resources and are divided as follows:
  - Zero-net buildings – the amount of the delivered energy is equal to the amount of the used energy;
  - Zero carbon buildings – do not use energy, which results in CO2 (carbon dioxide) emissions;
  - Zero stand-alone buildings – no need to be connected to the network, are accumulating energy for the night and winter;
  - Plus energy buildings – are producing more energy per year than it is consumed.

For the implementation of the housing energy efficiency programme, a contractionary factor can be the attraction of financing. Fundraising for the implementation of the housing energy efficiency programme without any obstacles/barriers is currently hindered by the following factors [10, p. 210]:

- consent of 51 % housing owners is required;
- utility debt;
- lack of motivation of low-income housing owners for the implementation of the object;
- uncertainty, both in terms of loan repayment and in terms of building energy efficiency benefits.

The interconnection between contractionary and motivating factors of sustainable development of real estate market and construction industry, which influence also the sustainable development of cities, is shown in Fig. 1.

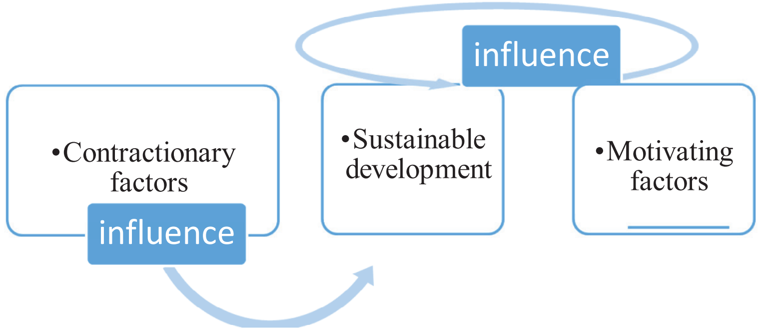


*Fig. 1.* Contractionary and motivating factors of sustainable development of real estate market and construction industry [made by the authors].

All mentioned aspects led to a necessity to develop sustainable industry regulation. To conduct the practical research on environmental aspects of sustainable real estate market and construction industry development in the Latvian context of sustainable development of industry and cities, the survey was developed on the basis of the previously conducted research.

*The aim of the survey* was to define the incentives and disincentives affecting green building development, its socio-economic importance and other issues related to the analysis.

*Research methodology:* quantitative research, online survey method (WAPI – web assisted personal interviews at Web panel). Research included 100 targeted largest companies in Latvia as was also in related methodology [9]. The areas of respondents' activity included real estate agencies, management of real estate on a fee or contract basis, development of building projects, construction of residential and non-residential buildings, civil engineering, renting and operating of own or leased real estate, buying and selling of own real estate. Structure of respondents was performed according to NACE 2.rev. classification [1]. Questionnaires were anonymous.

*Sampling:* The survey was focused on managers and employees of enterprises who were working in the real estate market (operating in the economic sector "Real Estate Operations" (L68) and "Construction" (F41)) such as managers and employee of real estate agencies, management of real estate on a fee or contract basis, development of building projects, construction of residential and non-residential buildings, civil engineering, renting and operating of own or leased real estate, buying and selling of own real estate. On 12 September 2017, the field of construction (F41) included 14639 enterprises, of which 5317 were related to construction of buildings (F41.1), and 13299 were enterprises dealing with real estate operations (L68) [1]. 100 respondents were selected, and only 18 respondents gave the responses. On average 78 % or 1 259 000 of the population of Latvia in the surveyed target group use the Internet on a regular basis [2]. The summarised information about the survey is shown in Table 1.

*Table 1*

**Information about the Survey [made by the authors]**

| Indicator | Description |
|---|---|
| Type of survey | Questionnaire |
| Description of experts | Experts operating in such areas as Real Estate Operations and Construction |
| The level of competence of respondents | Owner, top level manager, middle level manager, supervisory level manager |
| Responses | 18 |
| Period of questionnaire | From 1 August 2016 to 1 November 2016 (2016M8,M9,M10) |

Response rate was calculated as follows [13]:

$$\text{Response rate} = \frac{\text{Number of completed surveys}}{\text{Number of respondents contacted}} \quad (1)$$

"Internal surveys will generally receive a 30 %–40 % response rate (or more) on average, compared to an average 10 %–15 % response rate for external surveys" [11]. The same source shows that General Client Satisfaction Surveys are as follows: medium length – 15 %–30 % (with 1 follow-up) up to 25 questions" [11]. CustomInsight a US company that designs and administers surveys offered the following comments regarding the link between response rates and survey types: "Response rates vary widely for different types of surveys. Customer satisfaction surveys and market research surveys often have response rates in the 10 %–30 % range. Employee surveys typically have a response rate of 25 %–60 %. Regardless of the type of survey you are conducting, you can have a major effect on the number of respondents who complete your survey." [8]. *Not always lower replies are less valid,* there may be a relationship between whether a data point is missing and any values in the data set are missing or observed [12]; [6]. Environmental aspects of construction industry development are analysed in the subsequent section.

## 3. ENVIRONMENTAL ASPECTS OF CONSTRUCTION INDUSTRY DEVELOPMENT: A CASE OF LATVIA

According to the developed methodology, the survey was conducted. In the survey, 39 % respondents were owners, 11 % were high level managers, 17 % were middle level managers and 33 % were other company members, including front line specialists. Structure of respondents was as follows, according to NACE 2.rev. classification (European Commission, 2017):

L – Real estate activities;
L68 – Real estate activities;
L68.1 – Buying and selling of own real estate;
L68.1.0 – Buying and selling of own real estate;
L68.2 – Renting and operating of own or leased real estate;
L68.2.0 – Renting and operating of own or leased real estate;
L68.3 – Real estate activities on a fee or contract basis;
L68.3.1 – Real estate agencies;
L68.3.2 – Management of real estate on a fee or contract basis;
F41 – Construction industry.

Education level of respondents is shown in Table 2.

*Table 2*

**Education Level of Respondents, %**

| Education | % |
|---|---|
| Bachelor's degree/higher professional/higher | 55.56 |
| Master's degree | 33.33 |
| Secondary vocational | 11.11 |

The first question was related to the significance of each environmental factor for the construction of the environmentally-friendly and sustainable real estate object and its further operation (see Fig. 2).

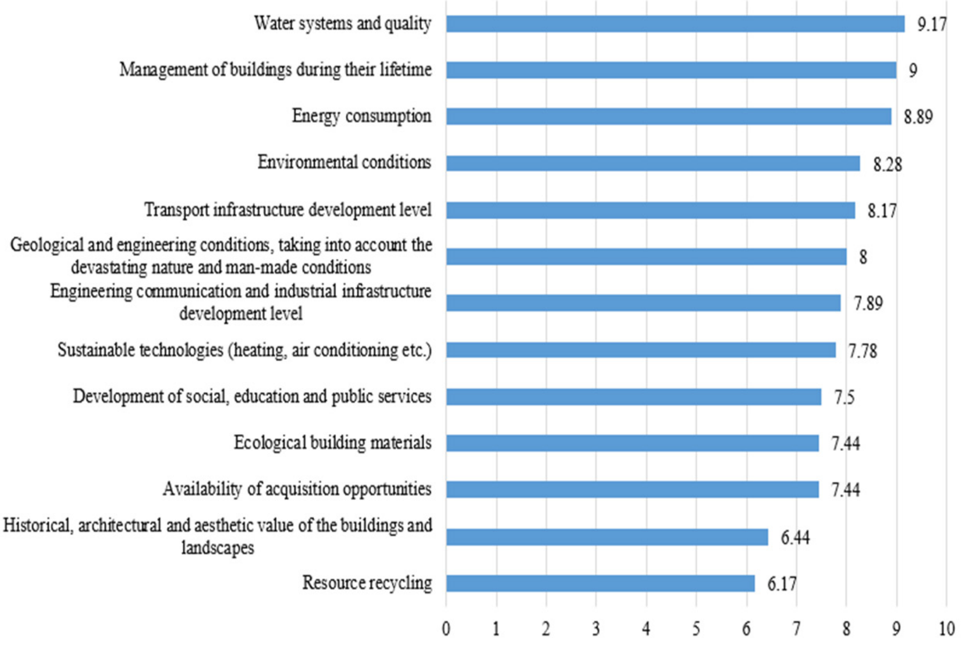


*Fig. 2.* What is the significance of each environmental factor for the construction of the environmentally-friendly and sustainable real estate object and its further operation? (1– not important, 10 – very important) [made and constructed by the authors].

Answers to the question "How do you evaluate the following factors influencing green building housing affordability" is shown in Table 3 (1 – not developed, negative evaluation, 10 – well-developed, positive evaluation).

*Table 3*

**Green Building Affordability [Made and calculated by the authors]**

| Factor | Average | St.dev. | St.err. | Median |
|---|---|---|---|---|
| 1. Price level of green building object | 5.06 | 1.92 | 0.1132 | 5.5 |
| 2. Mortgage loan (financing) accessibility for green building object financing | 6.00 | 2.38 | 0.1398 | 5 |
| 3. Per capita income | 4.56 | 2.62 | 0.1540 | 4 |

The average evaluation on question "How important are ecological aspects of civil construction?" was 711 points from 10 (0 – not important, 10 – very important).

The respondents also mentioned the following ecological aspects of construction that are important: huge amount of documentation and its approval in the state institutions, laws that promote ecology, the quality of the construction site. Some respondents mentioned the construction material quality, noise, dust, soil and waste water pollution, construction waste sorting need, proper disposal, nearby a mobile station. As the important aspects, the respondents mentioned the efficient use of resources, environmental quality problems, environmental impacts on health and well-being and the need to ensure the ecological and economically sound use of resources.

According to the survey results, more favourable conditions are important, the material security is a key issue; there is a need of confidence by investing. Green building investment has promoting and restrictive factors as well. Promoting and restrictive factors of green building investments are shown in Table 4.

*Table 4*

**Promoting and Restrictive Factors of Green Building Investments [table made by the authors] [Factor evaluation based on Riemenschneider, Kauškale (2016) [5]]**

| Promoting/motivating | Restrictive/obstructive |
|---|---|
| • Access to financing, regulations, mortgage rates (7.94)<br>• Available purchase price of the resources (7.83)<br>• Good overall economic situation in the country, economic upturn, contributing to an increase in demand (7.83)<br>• Good financial health opportunities, free assets (7.78)<br>• Favourable industry development trends (7.78)<br>• Successful investment attraction programmes (7.67)<br>• Green construction promotion national development policy (7.39)<br>• Competition in the industry, and hence the need for the construction of the competitive real estate object (7.28)<br>• Good Ease of Doing Business ranking* (7.11)<br>• Change in thinking paradigm of the buyers, focus on sustainability (6.94)<br>• Market pressure to find innovative opportunities (6) | • Lack of credit financing opportunities (7.78)<br>• Limited financial opportunities, lack of free funds (7.78)<br>• Lack of motivation (7.33)<br>• Lack of information (7.22)<br>• Lack of professional skills and professional employees (7.61)<br>• Lack of experience in green construction projects (7.5)<br>• Lack of management experience (7)<br>• Increase in the prices of resources (8)<br>• Economic recession, crisis contributing to a reduction in demand (7.11)<br>• Underdeveloped business environment (6.67)<br>• Increase in object selling price, which would reduce the potential number of buyers (7.67)<br>• Lack of long-term policies in the field of green construction (8.17)<br>• Competition in the industry (6.44)<br>• Low Ease of Doing Business Index (6.56)<br>• Difficulties to start operation (7.06) |

* Ease of Doing Business Index is an index developed and calculated by World Bank that ranks 183 countries according to ease of doing business in a particular country

The evaluation of the adequacy of knowledge for the successful green construction and sustainable construction entrepreneurship in the following areas showed the following results (see Fig. 3) (1 – no adequate skills; 10 – a lot of knowledge).

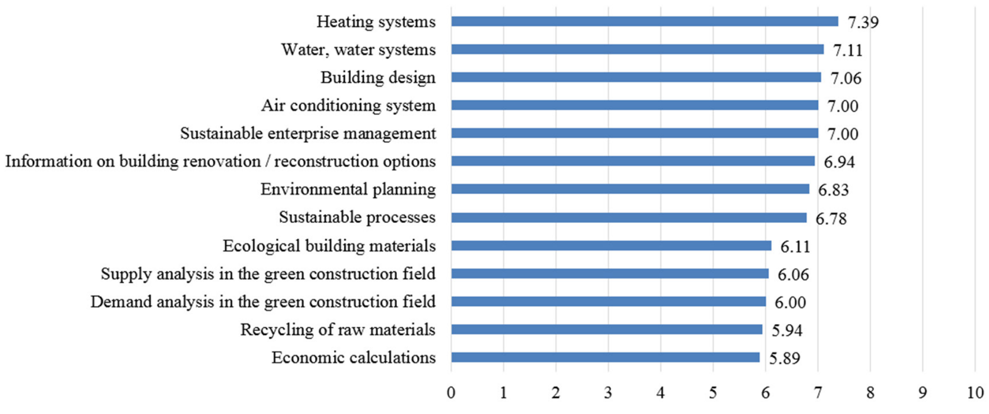


*Fig. 3.* The evaluation of the adequacy of knowledge for successful green construction and sustainable construction entrepreneurship (1 – no adequate skills; 10 – a lot of knowledge) [made and calculated by the authors].

The replies to the question "What kind of information is lacking and would be desirable for the successful operation in the green construction field?" included a lack of information on tax relieves and other relieves the green construction provides, a lack of information on the ecological construction materials, ultimate economy, fundraising opportunities, a lack of general knowledge, advertising and striving for the purest life. However, a lack of information was observed in all areas.

## 4. RESULTS AND DISCUSSION

The respondents of the survey gave the following recommendations: the introduction of tax relief and simplifying the construction process of green construction, work for the public sector together with the investment companies, encouraging green construction by law, promoting the state policy in this area, and concluding intention agreements. It is also necessary to know advantages of green building, the costs, its necessity and grounds for advantages, as a lack of information can be observed. Respondents could not find structured information on costs and energy-efficient solutions; no information was available on the definition of the concept; there was a lack of aggregated information from one resource, and the need arose to know the long-term benefits and impact on health. Local government should communicate more with the society and businesses. Work on macroeconomic stability should be continued, predictable changes (the number of laws, tax policies, etc.) should be provided, there is a necessity to build qualitative and aesthetic objects, while minimising the costs both in the construction and in the further maintenance of the object, as well as there is a need of price reduction to increase affordability of real estate and green buildings, or to increase average wages. BIM implementation, stable policy implementation, planning process rationalisation, advertisements and information of society, including energy performance certificates, successful use of the European Fund, investors' attraction, energy efficiency and sustainability indicators for buildings were also mentioned by the experts as important aspects for sustainable industry regulation that could influence city planning and its sustainability as well.

## 5. CONCLUSIONS

1. The results of analysis on sustainable entrepreneurship in construction companies resulted in high importance of ecological aspects of construction. Sustainable implementation of construction projects influences sustainable industry development, and these aspects are interconnected.
2. The research results highlighted a role of environmental information systems within the country that can be necessary for all market participants. The important aspects of sustainable entrepreneurship in construction industry are the efficient use of resources, the construction material quality, water pollution, the necessity of noise and dust minimization, construction waste sorting need, impacts on health and well-being and ensuring the sound use of resources from the ecological, economic and social point of view. The future research directions have been defined and are related to economic estimation of green building projects and their management aspects.

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## ILGTSPĒJĪGĀS BŪVNIECĪBAS NOZARES ATTĪSTĪBA UN ZAĻĀ BŪVNIECĪBA: LATVIJAS PIEREDZE

L. Kauškale, I. Geipele, N. Zeltiņš, J. Vanags

K o p s a v i l k u m s

Mūsdienās arvien vairāk tiek pievērsta uzmanība valsts ekonomikai, būvniecības nozarei un nekustamā īpašuma tirgus ilgtspējīgai attīstībai, kā arī pētījumiem, kas saistīti ar šiem jautājumiem. Pētījuma mērķis ir analizēt būvniecības un nekustamā īpašuma tirgus ilgtspējīgas attīstības būtiskos aspektus, īpašu uzmanību pievēršot vides aspektiem būvniecībā un zaļo ēku nozīmei tajā. Pētījumā ir iekļauta būvniecības nozares integrētās pieejas analīze un nekustamo īpašumu tirgu ietekmējošo aspektu analīze. Zinātniskie un praktiskie risinājumi un ieteikumi ļaus nozares dalībniekus iepazīstināt ar galvenajiem būvniecības nozares un zaļās būvniecības ilgtspējīgās attīstības jautājumiem, kas savukārt var uzlabot nozares vispārējo darbību ilgtermiņā.

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# HIGHLY RECONFIGURABLE BEAMFORMER STIMULUS GENERATOR

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The present paper proposes a highly reconfigurable beamformer stimulus generator of radar antenna array, which includes three main blocks: settings of antenna array, settings of objects (signal sources) and a beamforming simulator. Following from the configuration of antenna array and object settings, different stimulus can be generated as the input signal for a beamformer. This stimulus generator is developed under a greater concept with two utterly independent paths where one is the stimulus generator and the other is the hardware beamformer. Both paths can be complemented in final and in intermediate steps as well to check and improve system performance. This way the technology development process is promoted by making each of the future hardware steps more substantive. Stimulus generator configuration capabilities and test results are presented proving the application of the stimulus generator for FPGA based beamforming unit development and tuning as an alternative to an actual antenna system.

***Keywords:*** *antenna array, beamforming, LabVIEW, simulation, stimulus generator*

## 1. INTRODUCTION

Many technical applications before implementation into hardware are tested in the simulation mode achieving very close results to the real-life performance in order to have the desired hardware performance and resource economy, e.g., money, human power, time. Antenna array related technologies, such as radars are no exception and antenna array technologies become more and more common in different areas where their specific functionality is required, also implying that the performance of each component plays an important role in the antenna array system. The performance and characteristics of antenna array technologies are well known and have been studied for a few decades now [1], thus providing the necessary information to enable narrow band signal simulation of a receiver of the phased antenna array system.

The paper describes a phased antenna array stimulus generator, which includes specific parts of the antenna array system – an antenna array with a radio and intermediate frequency (RF/IF) path (LNA, amplifier, filter, mixer and ADC) and a beamformer.

Phased array antennas consist of multiple stationary antenna elements, which are fed coherently and use variable phase or time-delay control at each element to scan a beam to a given angle in space. The primary reason for using arrays is to produce a directive beam that can be repositioned (scanned) electronically [2].

A beamformer is a processor used in conjunction with an antenna array to provide a versatile form of special filtering for antenna array signal samples making the radar sensitive only to the selected direction [3]. Beamformers can be further subdivided into conventional beamformers and adaptive beamformers. Conventional beamformers employ a fixed set of the so-called weighting coefficients to combine signals from the antenna in the array, primarily using only information about the location of the signal of interest (SOI) relative to the antenna array, whereas an adaptive beamformer uses updated information about SOI and unwanted signals to reject them [4]. The paper presents implementation of a conventional beamformer with further development to be improved as an adaptive beamformer.

The most popular simulation environments, such as Matlab, use a sequential signal processing simulation model, graphical environment LabVIEW is convenient when it is to develop a parallel signal processing path[1]. LabVIEW provides a very convenient simulation environment for developing algorithms graphically from the perspective of electrical engineers, which is then well suited for development of simulation codes applicable in the most commonly used hardware for real-time high throughput signal processing – field-programmable gate array (FPGA). The greatest advantages of FPGA are the rapid non-stop technology development – increase in speed and parallel code execution, which will come relevant in the general concept when the hardware part will be developed. In the present paper, a general concept of stimulus generator application is explained, introduction to simulation reconfiguration capabilities provided and results presented.

## 2. GENERAL CONCEPT

Figure 1 presents the general concept under which the paper is developed. The concept has two utterly independent paths: Simulation path and Hardware path, where both paths can be combined at intermediate steps forming a half-simulated, half-hardware implemented antenna array receiver system. The main purpose of such a solution is to iteratively improve both paths using the simulated and real signals. The implementation of the four main steps for each path is different, but names are the same:

- Antenna array;
- Received signal;
- Beamforming;
- Beamformed signal.

[1] LabVIEW popularity (Accessed: 2 Aug 2017): http://ieeexplore.ieee.org/search/searchresult.jsp?newsearch=true&queryText=LabVIEW.

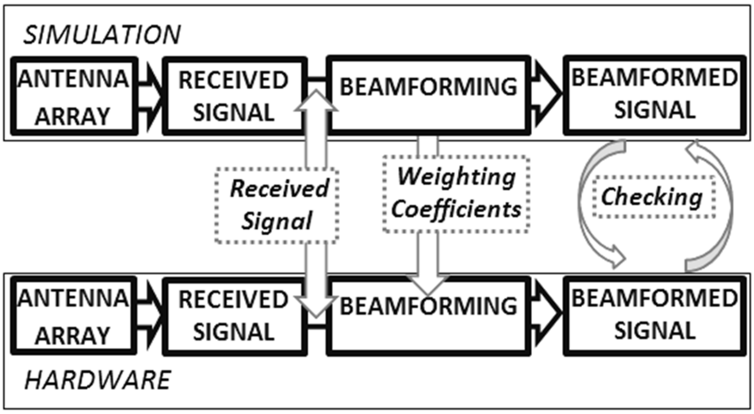


*Fig. 1.* Block diagram of a general concept.

*A. Simulation Path*

Simulation path steps are implemented and run in the simulation mode only, which means that characteristics of all the parameters must be simulated after a very close approximation of real-life. More importantly the developed simulation – the stimulus generator and beamforming simulation provide an opportunity to manipulate with each step and characteristics to find the most suitable design, parameters and performance for each individual implementation case and the desired application.

The first step defines the characteristics of antenna array; the second step "captures" the received signals from objects (signal sources) and saves them in a file to make stimulus for the FPGA based beamforming unit. In the third step, the weighting or beamforming coefficients are calculated and also saved in a file. Either of the files – simulated signal and weighting coefficients – can be imported in a hardware beamforming step, thus making it possible to develop FPGA-based beamforming unit signal processing algorithm without having an actual antenna array and an RF/IF path. This way the technology development process is promoted by making each of the hardware implementation steps more substantive.

In the final step, the beamformed signal is calculated approving or disapproving the estimated beamforming results. This is the step where performance of the complete system can be checked. The results of simulation path can be verified with the achieved results of hardware path calculating weighting coefficient corrections and consequently improving the performance of both paths [5].

*B. Hardware*

Hardware path steps are real-life based implementation, where an antenna array is a physical structure of a greater or a smaller dimension depending on the aim of application. Apart from tuning the beamformer, the received signals are recorded and saved in a file. Saved signals can be imported in the beamforming step of both signal paths to test the beamforming algorithm in both simulation and FPGA-based mode and check whether FPGAbased algorithm is working properly. Moreover, the received real life signals can be used to optimise the signal simulation step results taking into account new real-life signal amplitude-phase characteristics.

The third and fourth steps are utterly FPGA-based where the implementation is performed taking into account FPGA specification and limitations. Having the real-life received signal in the beamforming step of both paths, the beamformed signals can be compared to see if the results are consistent.

According to the topic of the paper from this point forward the paper focuses only on the simulation path.

## 3. SIMULATION

The simulation is developed in programming environment LabVIEW. The simulator consists of the three main reconfigurable steps (tabs of front panel are presented in Figs. 2–4):

### *A. Settings of Antenna Array*

Here (Fig. 2) antenna array characteristics, such as antenna radiating dimension, antenna array type (regular or irregular), number of antennas and distances between antennas, are set to simulate the desired antenna array.

Calculations regarding an antenna array include *x* and *y* coordinates for each antenna into an array (starting from bottom-left corner to top-right corner – through columns). In the case of a regular antenna array, coordinates are calculated from user defined distance between antennas *d(x)* and *d(y)* and the number of antennas per row and column. In the case of an irregular antenna array, coordinates are randomly generated from user defined maximum array length per *x* and *y* axis and the number of antennas.

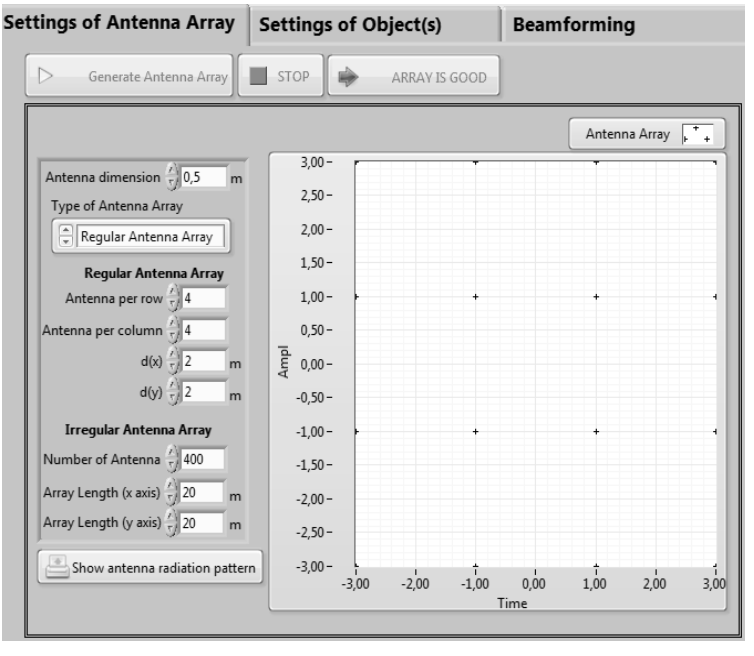


*Fig. 2.* Front panel of the developed simulation (Step 1).

*B. Settings of Objects*

In this tab (Fig. 3), characteristics of object or objects to be observed, such as object location, frequency and power, are configured to define the stimulus that antenna array will receive. It is possible to simulate up to four objects simultaneously, but it must be kept in mind that this simulator uses a conventional beamforming method.

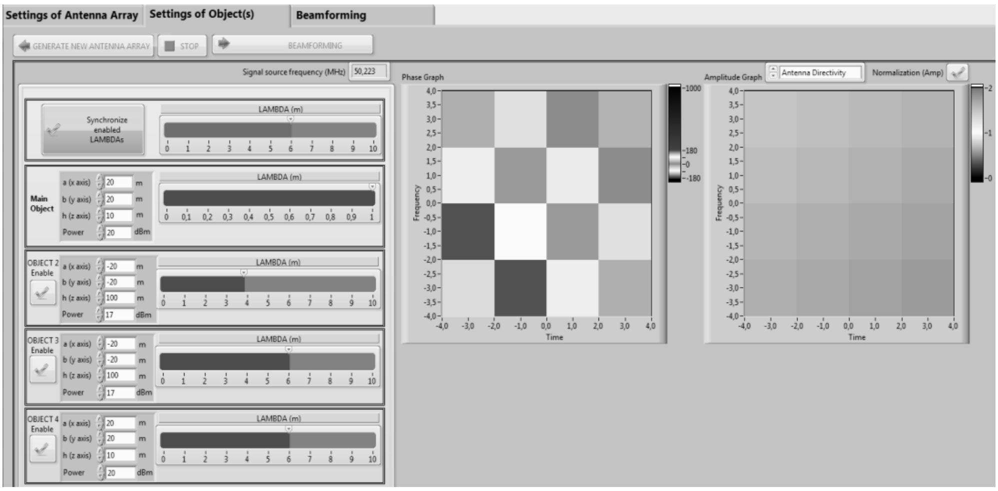


*Fig. 3.* Front panel of the developed simulation (Step 2).

a. Calculations regarding an Object

The distance between each antenna and object $S_{ant}$ *(x,y)* is calculated by the vector method. First, it is necessary to calculate $a'$ and $b'$ – the distance between each antenna and the object in x-y plane, where *a* and *b* is the distance between the centre of coordination system and the object in *x* and *y* axis, respectively, and $\Delta X(x)$ and $\Delta Y(y)$ is the distance between centre of coordination system and each antenna in *x* and *y* axis, respectively:

$$a' = a - \Delta X(x),\ b' = b - \Delta Y(y).$$

Calculation of distance $S_{ant}$ (x,y) using the distance between each antenna and object a' and b' and height (z axis):

$$S_{ant}(x, y) = \sqrt{a'^2 + b'^2 + h^2}.$$

b. Calculations regarding Antenna Array Signal Amplitudes

The amplitudes ($A_i$) of the received signals (object radiated power) for each antenna are calculated from an antenna directivity diagram *(D)* and as all antennas are identical dipole antennas they all have the same directivity diagram $A_i = D(a_i', b_i', h_i)$. It is possible to calculate antenna directivity depending on *h* (z axis) value and distance to the object in XY plane.

If $h = 0$ (the object is in XY plane):

$$D = \frac{1}{1+\left(\frac{b'}{a'}\right)^2}$$

If $h \neq 0$ (the object is not in XY plane):

if $|b'| \geq \sqrt{h^2 + a'^2}$ then

$$D = \frac{1}{1+\arctan\left(\frac{|b'|}{\sqrt{h^2+a'^2}}\right)}$$

if $|b'| \leq \sqrt{h^2 + a'^2}$ then

$$D = \frac{1}{1+\operatorname{arccot}\left(\frac{\sqrt{h^2+a'^2}}{|b'|}\right)}$$

c. Calculations regarding Antenna Array Signal Phases

The phases for each antenna are calculated from the distance between the object and antenna $S_{ant}$ (x,y) and the object signal frequency (wavelength λ). First the phases are calculated in radians $\varphi_{rad}$ and then converted in degrees $\varphi_{deg}$:

$$\varphi_{rad} = \frac{2\pi \times S_{ant}(x,y)}{\lambda},\ \varphi_{deg} = \frac{\varphi_{rad} \times 180}{\pi}.$$

*C. Beamforming*

In this step (Fig. 4), the generated signals are displayed: the main object signal, the received signals in each antenna, the beamforming signal and the beamformed signal. As an extra, signal path properties for standard deviation of the signal phase and amplitude can be configured.

Beamforming adjusts the amplitude and phase of each antenna array element signal to compensate for the different delays and attenuations associated with signal paths to elements to increase the signal quality in a specific direction of arrival [6]. This simulator has a conventional beamformer, where the weighting coefficients consider only SOI information: the signal amplitudes for each antenna are calculated from the free space path loss (FSPL) and other additional losses in the signal path, which can differ for each system; the signal phases are corrected for each antenna by changing the phase sign of the beamforming signal for each antenna [7].

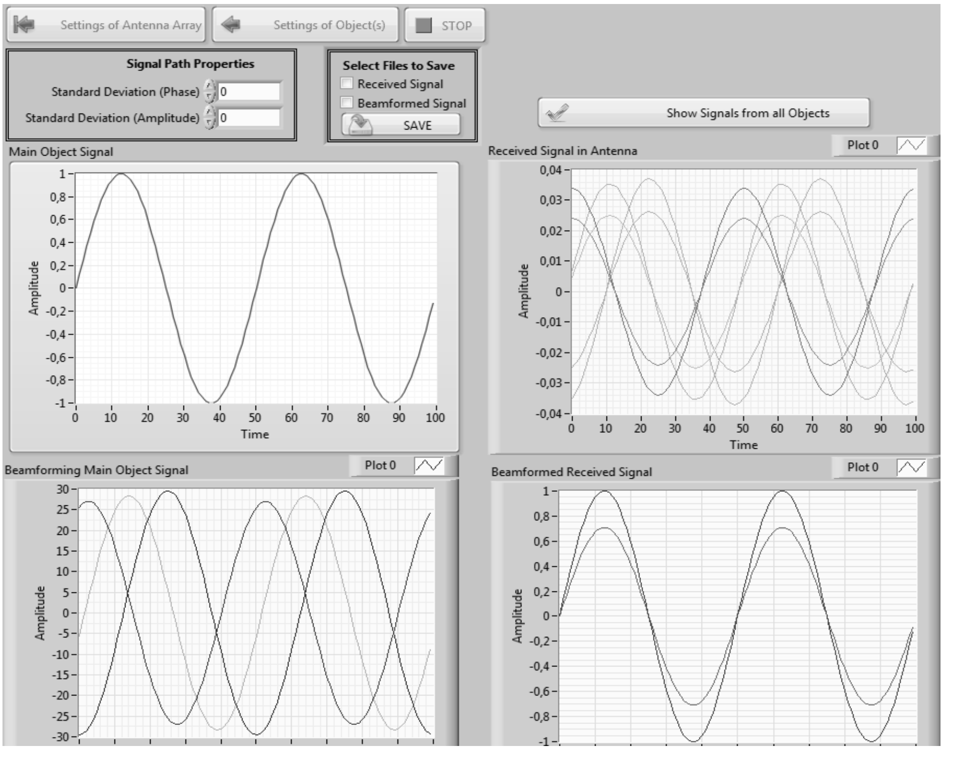


*Fig. 4.* Front panel of the developed simulation (Step 3).

The concept of the developed simulation is shown in Fig. 5, which demonstrates that the characteristics of stimulus are to be tweaked to represent the desired signals of the antenna array.


*Fig. 5.* Block diagram of the simulation concept.

When ready the received signal and beamformed signal can be saved in data files. The saved files contain data of generated signal, weighting coefficients and beamformed signal that can be applied in hardware implementation as a stimulus for checking and improvements of beamformer algorithm hardware implementation.

## 4. RESULTS AND DISCUSSION

The simulation path has been created by developing the stimulus generator of radar antenna array; the algorithms initially have been tested in LabVIEW simulation mode. The testing is done by analysing the achieved results and saved signal files. All simulation results are shown in the simulation software graphs and indicators allowing one to check simulation model correctness.

The performance of the stimulus generator was evaluated simulating different antenna arrays and checking the generated signals qualitatively and quantitatively. As an example, Fig. 6 demonstrates simulation of a regular antenna array (Fig. 6) with 4 x 4 antennas (numbering starts from bottom-left corner to top-right corner – through columns) with 2 meter distance among antennas. In the array, all the antennas are identical dipoles and positioned in parallel to *y*-axis with radiating dimension of 0.5 meters. The SOI is an object with radiating power of 20 dBm and initially located 5 meters above the centre of XY plane. During simulation, the position of the object is changed for each of the four tests:

1. Position A (meters): x=0; y=0; z=5;
2. Position B (meters): x=5; y=0; z=5;
3. Position C (meters): x=5; y=5; z=5;
4. Position D (meters): x=0; y=5; z=5.

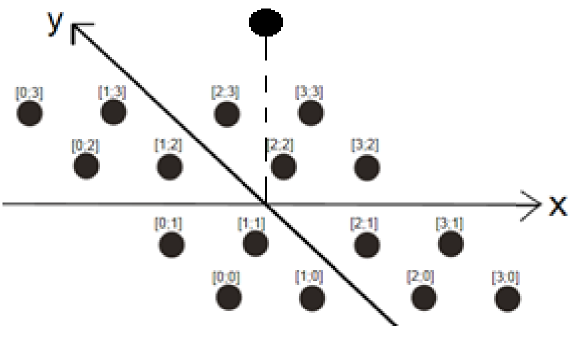


*Fig. 6.* Signal simulator setup.

The result of this test and, accordingly, the performance of this stimulus generator are shown in Fig. 7, where the characteristics, such as phase and power, in the antenna array are presented. The difference in phase and power when changing the object location meets the expected results, because when object is initially located in the centre of array the antennas located closer to the object in XY plane will have greater power than the ones located further in either of the directions in *x* or *y* axis. The same principle is observed for all four tests. From these results it can be concluded that the signal simulator is working correctly and as expected.

In order to test the inverse-square law in the performance of one antenna array row from the same antenna array setup as previously, five different object locations are set to measure the received power in each antenna in row. The distance between the object and the nearest antenna ranges from 1 to 26 meters and the radiated power of the object remains constant 20 dBm. The result is presented in Fig. 8, where the power over distance decreases with the object being moved further away from the antenna array.

Similar simulations (not described here) can be made to prove the simulation correctness simulating multiple signal sources (up to 4) or random antenna arrays.

**Signal Characteristics in Antenna Array**

| x axis, m | 0 | | 5 | | 0 | | 5 | |
|---|---|---|---|---|---|---|---|---|
| y axis, m | 0 | | 0 | | 5 | | 5 | |
| Antenna No | Power dBm | Phase Deg | Power dBm | Phase Deg | Power dBm | Phase Deg | Power dBm | Phase Deg |
| 00 | -28.79 | -34.84 | -32.37 | 23.88 | -28.25 | -147.45 | -32.14 | 76.24 |
| 10 | -27.90 | -86.06 | -32.00 | -112.32 | -29.44 | -137.22 | -32.67 | 81.69 |
| 20 | -27.90 | -86.06 | -32.00 | -112.32 | -30.91 | -19.37 | -33.42 | 124.07 |
| 30 | -28.79 | -34.84 | -32.37 | 23.88 | -32.37 | 23.88 | -34.30 | 113.78 |
| 01 | -27.90 | -86.06 | -30.91 | -19.37 | -27.23 | 106.22 | -30.58 | -25.34 |
| 11 | -26.77 | 128.23 | -30.38 | 108.29 | -28.69 | -127.07 | -31.32 | 111.66 |
| 21 | -26.77 | 128.23 | -30.38 | 108.29 | -30.38 | 108.29 | -32.32 | -37.00 |
| 31 | -27.90 | -86.06 | -30.91 | -19.37 | -32.00 | -112.32 | -33.42 | 124.07 |
| 02 | -27.90 | -86.06 | -29.44 | -137.22 | -27.23 | 106.22 | -28.99 | 146.44 |
| 12 | -26.77 | 128.23 | -28.69 | -127.07 | -28.69 | -127.07 | -30.01 | 78.48 |
| 22 | -26.77 | 128.23 | -28.69 | -127.07 | -30.38 | 108.29 | -31.32 | 111.66 |
| 32 | -27.90 | -86.06 | -29.44 | -137.22 | -32.00 | -112.32 | -32.67 | 81.69 |
| 03 | -28.79 | -34.84 | -28.25 | -147.45 | -28.25 | -147.45 | -27.64 | 67.68 |
| 13 | -27.90 | -86.06 | -27.23 | 106.22 | -29.44 | -137.22 | -28.99 | 146.44 |
| 23 | -27.90 | -86.06 | -27.23 | 106.22 | -30.91 | -19.37 | -30.58 | -25.34 |
| 33 | -28.79 | -34.84 | -28.25 | -147.45 | -32.37 | 23.88 | -32.14 | 76.24 |

*Fig. 7.* Generated signal of 2D antenna array.

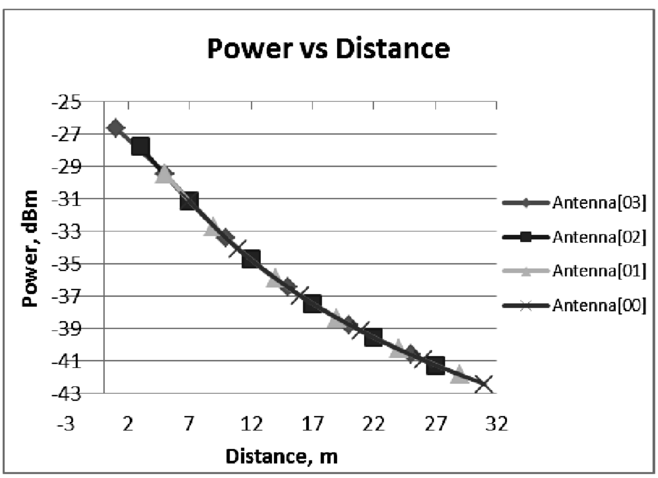


*Fig. 8.* Power vs distance.

## 5. CONCLUSIONS

System development in the simulation mode is a very convenient way to test the performance of the system to be implemented into hardware and to promote the progress of hardware design development process. None the less, the simulation mode in any aspect is less resource consumable.

The result of research described is a highly reconfigurable stimulus generator of antenna array receiver that is implemented into National Instruments PXIe1075/8133 platform with the main stimulus generation parameters:

1. Practically unlimited number of simulated antennas;
2. Regular and random placement of antennas;
3. Four different configurable (signal wavelength, power, position) sources of observable objects where one is always the main object and three are unwanted (parasitic noise) signals;
4. Ability to save the generated signals and weighting coefficients of antennas in files.

The stimulus generator is tested and approved by mathematics to be working correctly. It can generate the received signals in an antenna array with characteristics of real-life signals. The generated stimulus and the weighting coefficients can be imported in a hardware beamforming unit, e.g. FPGA-based, to test the hardware implementation without an actual antenna array, which is the main advantage of this simulator. When both simulation and hardware systems are developed, the interaction between these system steps becomes very useful for verification and improvement of both systems.

Future research includes improvement of the simulator by developing an adaptive beamformer and development of a hardware beamformer using National Instruments PXIe-7965R Xilinx Virtex 5 SX95T FPGA Board.

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## DAUDZPARAMETRU PĀRKONFIGURĒJAMS STARA FORMĒŠANAS STIMULA ĢENERATORS

E. Vaviļina, G. Gaigals

K o p s a v i l k u m s

Pirms praktiski īstenot tehniskos risinājumus resursu taupīšanas nolūkā - tie lielākoties tiek vispirms pārbaudīti simulācijas vidē. Antenu lauka tehnoloģijas tiek pētītas jau vairākus gadu desmitus, tāpēc ir pieejama detalizēta informācija par to darbības principiem un ir iespējams izstrādāt antenu lauka uztvērēja signāla simulāciju stara formēšanai. Šajā rakstā tiek prezentēts daudzparametru pārkonfigurējams stara formēšanas stimula ģenerators un stara formēšanas simulācija. Stimula ģeneratoram var konfigurēt antenu lauka tipu, izmēru, antenas maksimālo fizisko izmēru, antenu skaitu, uztverto objektu skaitu, lokāciju un jaudu, kā arī veikt tā stara formēšanu simulāciju. Simulators ir izstrādāts LabVIEW, kas ir viegli savietojama programmēšanas vide ar FPGA bāzētu aparātnodrošinājumu. Ģenerētos stimulus un antenu signāla korekcijas koeficientus var saglabāt failā, lai vēlāk tos pielietotu, izstrādājot stara formēšanas bloku FPGA bāzētā programmaparatūrā. Tas stipri atvieglo aparatūras staru formētāja izstrādi, jo izstrādātais antenu lauka signālu simulators aizvieto fizisku antenu lauku.

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*APPLIED PHYSICS*

# AN ICE TRACK EQUIPPED WITH OPTICAL SENSORS FOR DETERMINING THE INFLUENCE OF EXPERIMENTAL CONDITIONS ON THE SLIDING VELOCITY

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The ability to slide on ice has previously focused on the measurement of friction coefficient rather than the actual sliding velocity that is affected by it. The performance can only be directly measured by the sliding velocity, and therefore the objective was to design and setup a facility to measure velocity, and determine how experimental conditions affect it. Optical sensors were placed on an angled ice track to provide sliding velocity measurements along three sections and the velocity for the total sliding distance. Experimental conditions included the surface roughness, ambient temperature and load. The effect of roughness was best reported with a Criterion of Contact that showed a similar sliding velocity for metal blocks abraded with sand paper smoother than 600 grit. Searching for the effect of temperature, the highest sliding velocity coincided with the previously reported lowest coefficient of ice friction. Load showed the greatest velocity increase at temperatures closer to the ice melting point suggesting that in such conditions metal block overcame friction forces more easily than in solid friction. Further research needs to be conducted on a longer ice track, with larger metal surfaces, heavier loads and higher velocities to determine how laboratory experiments can predict real-life situations.

***Keywords:*** *ice friction, inclined plane, measurement approach, sliding on ice, sliding velocity, surface roughness*

## 1. INTRODUCTION

Studies on sliding over ice have predominantly measured a friction coefficient over an inherently unstable ice surface – the measurement of friction and the unstable ice surface have slowed progress. An approach giving a measure of sliding needs to be introduced concurrently with a deeper understanding on the changes of ice after passage of a sliding object. The present research will discuss an alternative test to the measure of ice-friction as an indicator of the performance.

Most tests have been conducted within a laboratory setting to quantify the friction responsible for movement over ice. Apart from several uncommon methods such as shear strength, adhesion and stick-slip tests [1]–[4], the most popular ones such as ring-on-disk [1], [5]–[7] or pin-on-disk [8] tests move a material surface repetitively over the same ice path and therefore modify the ice surface with a thin layer of water [6], [9] leading to a departure from an initial ice condition. Sliding over fresh ice has been made possible by moving the sliding object over a spiral path [10]. Other tests have used a linear tribometer for measuring the ice friction [11]–[14]. In these situations, the object is not free to move over ice, but is fixed to a mechanism that controls testing conditions (such as load and velocity) and measures the ice friction. Ice friction is then used to predict the performance instead of measuring the sliding time, or calculating the sliding velocity, both of which are directly related to the performance.

Studies of sliding over ice have seldom used the materials engineering paradigm that considers a material microstructure, determines the properties and then seeks a relationship with the performance. Ice friction, the material property of interest, has been the main focus of studies to differentiate between different material geometries, contact profiles and materials surfaces in contact with ice. An alternative way of assessing improvements in the sliding over ice could be to look at the sliding time or the sliding velocity as performance indicators. Focusing studies on the performance will provide clearer indicators of testing conditions and material surfaces that lead to better results, narrowing down the test conditions or material surfaces that need more detailed investigation.

The present research will consider sliding down an angled surface to evaluate movement over ice in laboratory conditions. Interaction with ice will be over relatively fresh ice that is more representative of material interaction with ice than the thin water film that remains from the previous interaction with ice. The use of sensors along the sliding path will show the sliding velocity at different distances, allowing the interaction with ice to be assessed at different velocities.

In order to measure movement over ice, we propose measuring the movement of an object down an angled ice surface. This test setup could be used to determine the static ice-friction as well as the sliding velocity at different test conditions (temperature, humidity, load, surface wettability, surface roughness, etc.). Two different type experiments could be conducted:

1. *Determination of the static friction coefficient.* The sample is placed on a horizontal ice surface and one end is slowly raised until a critical angle $\alpha$ is reached when the sample starts moving. The static friction coefficient can be calculated as the tangent of the angle $\alpha$ as known from basic physics. This requires an accurate method of measuring the angle of the plane because angle differences between similar surface treatments might be difficult to notice;

2. *Determination of the sliding velocity.* The time is recorded for samples (with the same geometry and weight) that move down an inclined ice plane past motion detection sensors for calculating the velocity at different distances (Fig. 2). The use of a gate opening mechanism minimises the influence of the operator.

The static friction coefficient measurement has been commonly used for centuries, and it is well known to everyone who has studied basic physics, but the use of an inclined plane for determining sliding ability is rarely discussed, especially in the field of ice friction; therefore, the present research is focused on measuring the sliding velocity.

The objective of the research is to determine whether sliding down an angled ice surface provides a useful indicator of sliding over ice for choosing conditions for better sliding times. Test conditions representing the environmental conditions (ambient temperature), the sliding object (load and surface roughness) will be altered to investigate the sliding velocity.

## 2. MATERIALS AND METHODS

### *Preparation of the Ice Track*

Ice was prepared by pouring hot water (~ 70 °C) into a U-shaped profile and freezing 5 layers to build up the total thickness of 30 mm with the goal of achieving homogeneous ice without cracks and air inclusions. The time necessary for freezing at -10 °C was approximately 48 h.

A guide track (groove) was made by planning the middle of the track to a flat surface with U-shaped walls so that the sample slid a similar path without possibility of rotating (inset of Fig. 2). The central lower sliding path ensured that the blocks did not touch the sensors or profile metallic sides and protected block from falling out of the track. Loose debris arising from the planning operation was removed with a moist sponge. Afterwards the track was left untouched during the experiment.

### *Preparation of the Blocks*

Stainless steel samples (made 35 mm long, 18 mm wide and 14 mm high) were milled from austenitic-ferritic steel (containing 82.6 % Fe, 0.12 % C, 13.4 % Cr, 1.6 % Ni, 1.3 % Mn, 0.2 % Si, 0.2 % V and 0.1 % S) to a weight of 67 ± 0.5 g. The blocks were then polished on a *334 TI 15 semi-automatic polisher* (Mecatech, UK) to an average surface roughness, *Sa* of ~ 8 nm. The surfaces were then modified with parallel scratches by abrasion under a load of 10 N on sandpaper (grit designations of 400, 600, 2000 and 3000). Scratches were made by moving the block in a forward and backward direction for a total distance of 2400 mm [15].

### *Characterisation of the Surface Roughness*

Since the surfaces contained directional roughness, the surface roughness measured in 3D is more appropriate to obtain the roughness along the scratches instead of a 2D roughness that typically measures the roughness perpendicular to a scratch direction. Previous research not only showed that a 2D measure was insufficient [15], but further indicated that a 3D measure needed a more detailed representation, such as the Criterion of Contact (*CCr*). Consideration of the surface roughness term in CC, labelled as *CCr* for sliding on ice, is the following:

$$CC_r = \frac{R_{Sm}}{S_a}, \tag{1}$$

where $CC_r$ – the roughness parameter component of the Criterion of Contact;
$R_{Sm}$ – mean spacing between roughness asperities at the mean line, measured in movement direction (mm);
$S_a$ – arithmetical mean height of the surface asperities (μm).

The roughness characterisation using *CCr* combines roughness measure in the vertical direction (*Sa*) with roughness measure in the horizontal direction ($R_{Sm}$) forming a ratio that characterises the average steepness of the asperities (Fig. 1). A larger ratio represents flatter asperities (smoother surface), but a smaller ratio – steeper asperities (rougher surface).

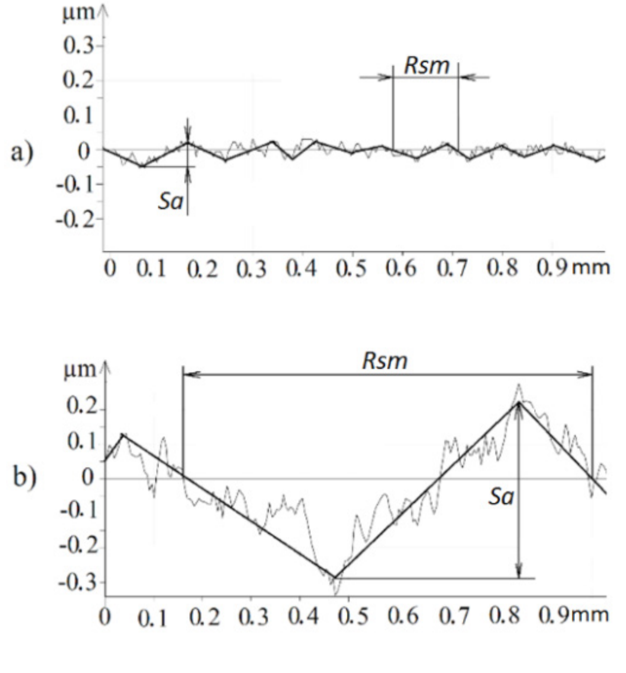


*Fig. 1.* A schematic of the Criterion of Contact for:
a) polished surface; b) surface abraded with 400 grade sandpaper.

Surface roughness was measured by *Form Talysurf Intra 50* profilometer (Taylor Hobson, UK) with a *112/2009 stylus* (2 μm tip) at a speed of 0.5 mm/s and cut-off of 0.25 mm. 400 parallel profiles were taken in a 2 x 2 mm area [15].

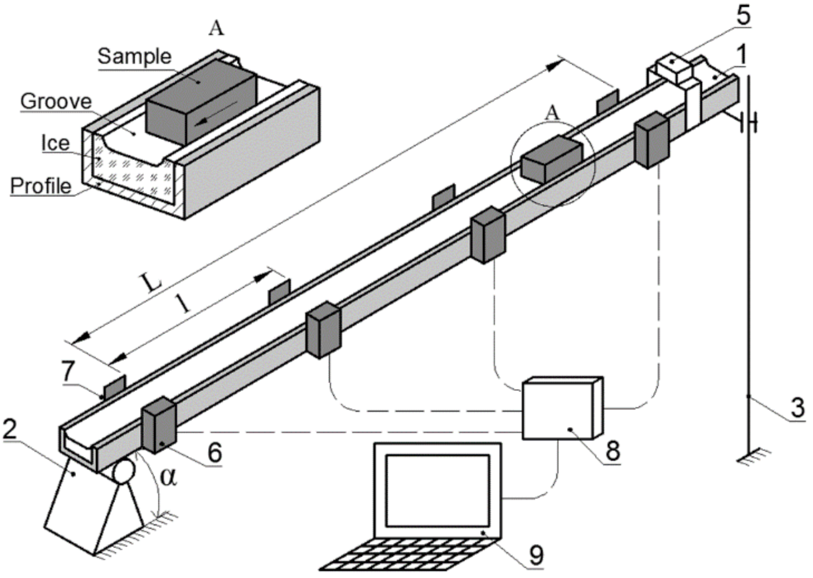


*Fig. 2.* Setup for measuring the sliding velocity of a metal block down an ice track.

The ice track was free to rotate at one end and fixed at the opposite end to set the angle α for sliding experiments. The start gate was raised by an electromagnetic actuator to allow the block to start sliding freely, without influence from the operator, and move past the first optical sensor, where the start time was logged, and sensors 2, 3 and 4 to determine the time and hence the sliding velocity at each distance (Fig. 2). Sensors were positioned 1100 ± 1mm between each other and the total distance, L was 3300 ± 1mm. Optical sensors *SOEG-RSP-Q20-PS-S-2L* (Festo, GER) sent the signals to the *FluidSIM input/output* (Festo, GER) collection module and then to the *EasyPort* (Festo, GER) interface and further to the computer where calculations were made for the sliding velocity at each distance. The equipment measured sliding time with an accuracy of 0.01 seconds.

The sliding angle, selected as 16° higher than the minimum to initiate sliding, was kept constant to provide a comparison of sliding velocity from differently prepared blocks. The block glided down the ice slope and passed by the 2nd, 3rd and 4th set of optical sensors to provide an average velocity relative to the earlier optical sensor, positioned 1100 mm further up the ice track. The average velocity in each section as well as the entire distance was then calculated.

The first experiment considered the use of the ice track, but the remaining three experiments investigated the influence of experimental conditions on the sliding velocity. In the experiment on the use of the sloping ice track, the sliding velocity was determined at different distances. The other three experiments looked at the impact of experimental conditions on the sliding velocity – the sliding block surface condition, the temperature and the load on the sliding block. Eighty measurements were made for each test sample.

*Table 1*

**Conditions for Evaluating the Effect of Temperature, Roughness and Load on the Sliding Velocity**

| Experimental condition | Effect of roughness | Effect of temperature | Effect of block load |
|---|---|---|---|
| Temperature, (± 1 °C) | -5.5 | -13.0; -8.0; -3.0 | -8.0; -5.5; -3.0 |
| Block surface treatment | Polished, 3000, 2000, 600, 400 | Polished; 3000; 600 | Polished, 600 |
| Block load, (± 1 g) | 67 | 67 | 67; 127; 157 |
| Number of blocks | 13 | 6 | 4 |

The first experiment examined the average velocity in the upper third, the middle third and the lower third sections of the ice track. For this experiment, all four sets of sensors were used. Ambient temperature was set to -5.5 °C. The average velocity over the entire length was then determined and closer attention was given to the effect of experimental conditions on the sliding velocity.

Since the metal surface roughness would affect ice friction, roughness was addressed first condition for more detailed testing. Surfaces were abraded with 400 grit sand paper at one extreme, or polished on an auto polisher at the other extreme. This experiment reduced the number of surface roughness conditions in further experiments. The same experiments were performed 3 times on different days to assess repeatability.

The effect of ambient temperature on sliding velocity was then investigated at three different surface roughness conditions. The end points were chosen at -13 °C for close to dry friction and at -3 °C for friction including a significant water interlayer whose thickness due to the lack of specific equipment was not measured.

Finally, three different block weights were chosen. The first block with a size of 35 mm long, 18 mm wide and 14 mm high was left as it was but the blocks with heavier weights had an additional block with identical geometry placed on top of them. To produce the same dimensions for additional blocks, the heaviest one was made of lead but lightest one from the same stainless steel as basic blocks.

## 3. RESULTS AND DISCUSSION

The arrangement of four sensors along the ice track provided four different measures of the sliding velocity. An average velocity was reported for each section, and an average velocity for the full length of the ice track (Fig. 3). It appeared that the increase in velocity within the second section was slower than the first section, but increased more than twofold in the third section. The range of velocity from 1.4 m/s to 5.2 m/s covered the mid-range of velocities investigated by other researchers [5], [7], [10], [13]. Arranging the sensors closer to each other will tend to instantaneous velocities tending towards 10 m/s, the maximum reported by others. As a result, this test facility provides a test setup that would be comparable to the previous ice friction studies.

This sliding velocity test facility is flexible in that it can measure the velocity at any location along the ice track by changing the location of the sensors. Additional sensors may also be selected to provide more sliding velocities at selected locations.

Abrasion with sand paper influenced the sliding velocity. In all cases, the metal block abraded with 2000 grit sand paper showed the fastest sliding velocity (Fig. 3). This suggests that smoother surfaces do not necessarily slide faster. A close examination of the average velocity in the last section of the ice track showed that a slightly rougher metal block glided at a velocity comparable to the 2000 grit sand paper surface. This makes the 600 grit abraded metal block worthy of closer attention, and so was included in further experiments.

The effect of surface preparation was best represented with the Criterion of Contact to show the influence on sliding velocity (Fig. 4). The average peak height represented by *Sa* shows a weak correlation with the sliding velocity and it is noticeably difficult to show comparison of similar smooth surfaces with rougher ones at the same graph (Fig. 4a). Results showed that a maximum sliding velocity was reached when the surface asperities were significantly flat but with less contact area than polished surface had (Fig. 4b). At $R_{Sm}/S_a > 700$, the average sliding velocity over the entire length of the ice track showed a plateau.

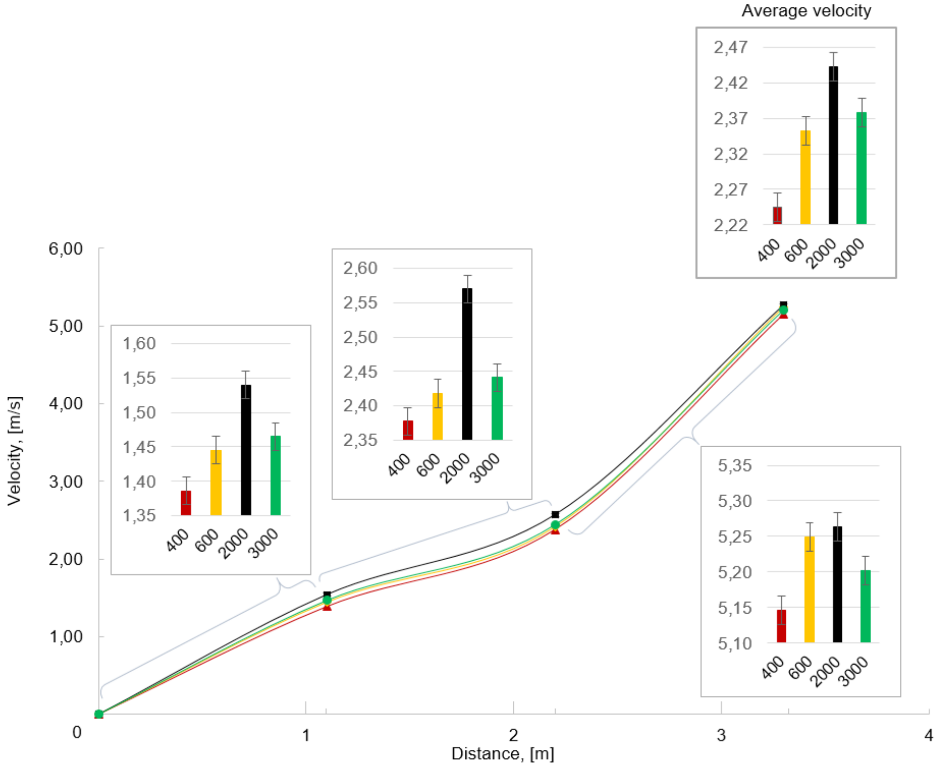


*Fig. 3.* The average velocity within the three sections and the total length of the ice track. Insets show the sliding velocity of metal blocks abraded with 400 grit, 600 grit, 2000 grit and 3000 grit sandpaper.

Along with the point of contact there is the effective stress of the peaks on the ice surface. When there are fewer and steeper peaks interacting with the ice surface, then peak height will become more important for determining the stress imposed by the peaks that dig into the ice. A larger stress by the steeper peak will slow the movement on ice.

The 2000 grit, 3000 grit and polished surfaces showed a comparable velocity when testing at an ambient temperature of -5.5 °C.

The ambient temperature caused a further change in the sliding velocity. Previous experiments showed comparable sliding velocities at -5.5 °C. Testing at colder conditions (at -13 °C) led to an overall decrease in sliding velocity, and more similar sliding velocities, but an increase in temperature to -3.0 °C reduced the sliding velocity, and separated the results more clearly (Fig. 5). These results are similar to the ice friction measurements determined by others, showing a minimum between -8 °C and -3 °C. The smallest ice friction will be associated with a larger acceleration and a resulting larger velocity. The minimum in ice friction should then directly correlate with a maximum acceleration and the highest velocity.

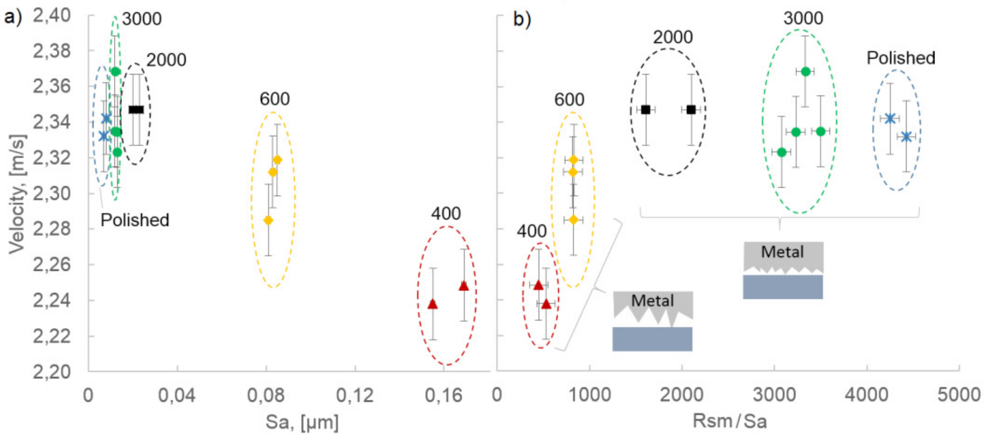


*Fig. 4.* Influence of the metal contact with ice on the average sliding velocity (modified from [15], there are few studies on friction of metal with smooth surfaces such as ice. The aim of this study was to determine the best surface roughness measure that correlates with the ease of sliding. Ice was chosen as the smooth surface since it is easy to produce. Stainless steel blocks were abraded with different grades of sandpaper to produce parallel scratches in the metal surface. Single roughness measures (Ra, Sa, SSk, Sds, Sdq, and RSm) shown with: a) the surface toughness $S_a$; b) the Criterion for Contact roughness parameter ratio $R_{Sm}/S_a$).

A change in ice friction has been correlated with a water film present at the sliding interface. Greater friction occurs from solid ice friction (the movement of metal against ice) but the introduction of a water film reduces the friction. This faster sliding velocity shown in laboratory test conditions is supposedly linked to a thin water layer. Even though everyone agrees that such a layer exists, there is still no unified and safe method for measuring the thickness of this layer.

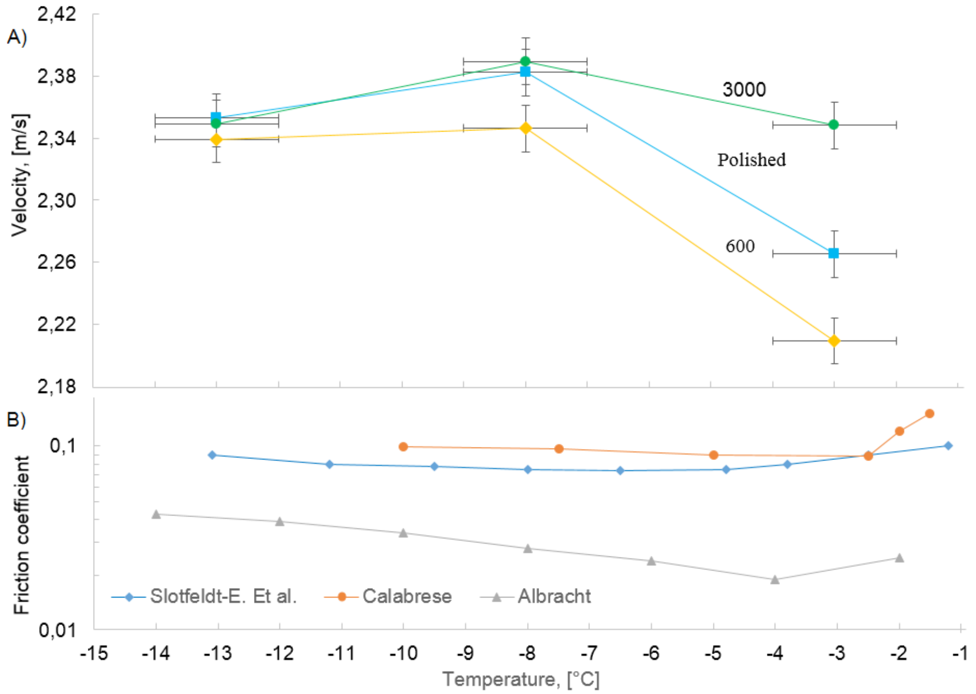


*Fig. 5.* Influence of temperature on the average sliding velocity, compared to the ice friction determined by others [5]. A minimum in ice-friction will be associated with a larger acceleration and hence a higher velocity.

A thicker film then creates viscous drag to slow the movement of the metal on ice. The viscous drag could possibly explain the pronounced reduction in sliding velocity for the polished surface that would have the best wetting conditions. It appears that a slight roughness, as shown by the 3000 abrasion, aids the sliding on ice if small contact pressures are applied to contacting surfaces.

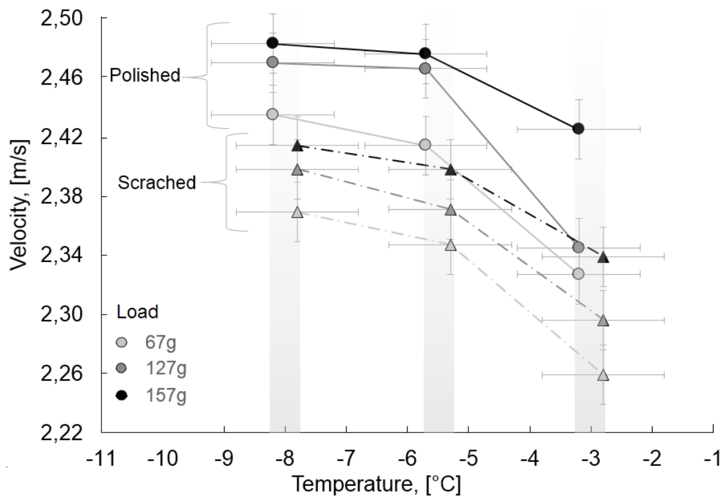


*Fig. 6.* The influence of load on the sliding velocity of polished and 600 grit roughened metal blocks at -8.0 °C, -5.5 °C and -3.0 °C.

A load on the sliding metal block increased the sliding velocity for both polished and 600 grit abraded surfaces. The total effect from an increase in load cannot be seen since the air drag for larger block geometry is presently not known, which decreases the sliding velocity. Regardless of the air drag, a greater load introduced a larger potential energy that was expected to result in a greater velocity. It is noteworthy that temperature close to the melting point of ice results in a greater increase in velocity that suggests that a heavier load overcomes viscous drag of the water more effectively at -3 °C than the solid friction at -8 °C.

The sliding velocity measured within the laboratory with four sensors on the ice track showed the ability to clearly distinguish the effect of surface abrasion, temperature and load. Given that the sliding conditions at the metal-ice interface may change with velocity, this setup will allow a closer study of sliding velocity at different distances and within specified distance intervals by changing the location of the sensors. Alternatively, additional sensors can be added to provide a larger number of sections available for the analysis.

This setup used flat metal blocks leading to more pronounced effects. A large contact area provided interaction of the metal surface with the ice. Viscous drag in these conditions is thought to have been greater compared to cylindrical pieces that result in a lower degree of interaction. Testing at the laboratory scale can also be conducted on a mini sled like arrangement with two runners that would require a wider ice track. This degree of flexibility with the sample geometry and ability to determine the sliding velocity as a performance measure velocity offers a valuable measure for quickly comparing different conditions to narrow down the number of blocks or experimental conditions that can be subjected to a more detailed investigation.

## 4. CONCLUSIONS

The setup for measuring the sliding velocity provided an average sliding velocity at each of the distance intervals, and also along the full length of the ice track. The velocity of the metal block at different locations could be used to determine how experimental parameters influenced the sliding velocity at different distances. The average sliding velocity over the entire length showed that a) surfaces abraded with sandpaper smoother than 600 grit slid similarly, b) higher sliding velocity occurred at a temperature that coincided with the previous measurements of ice friction and c) an increase in the load led to faster sliding especially at temperature closer to the melting point of ice.

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# EKSPERIMENTU UZSTĀDĪJUMU IETEKMES UZ SLĪDĒŠANAS ĀTRUMU PĒTĪJUMI IZMANTOJOT LEDUS PLAKNI AR OPTISKAJIEM SENSORIEM

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## Kopsavilkums

Līdzšinējie pētījumi, kuros apskatīta objektu spēja slīdēt pa ledu, pamatā orientēti uz berzes koeficienta noteikšanu, nevis slīdēšanas ātruma izmaiņu noteikšanu. Tā kā materiāla funkcionalitāti labāk izsaka tā slīdēšanas ātrums, nevis berzes koeficients, šī pētījuma ietvaros tika izveidota mērīšanas sistēma, kura ļauj noteikt paraugu slīdēšanas ātruma izmaiņas, kā arī ļauj novērtēt dažādu eksperimenta uzstādījumu ietekmi uz ātruma izmaiņu. Iekārta izveidota kā slīpā plakne, kuras sānos piestiprināti optiskie sensori, kuri ļauj veikt vidējā slīdēšanas ātruma noteikšanu plaknes trijos starpposmos, kā arī visas distances garumā. Tika apskatīts vai ar iekārtas palīdzību iespējams noteikt slīdošā parauga raupjuma, gaisa temperatūras un pieliktā svara ietekmi uz slīdēšanas procesu. Virsmas raupjuma raksturošanai izmantots kontaktkritērijs, kurš uzrāda, ka virsmas, kuras sagatavotas ar smalkāku smilšpapīru par 600. marku, uzrāda ļoti tuvus slīdēšanas ātrumus. Apskatot temperatūras ietekmi, novērots, ka lielākais slīdēšanas ātrums vērojams līdzīgā temperatūru diapazonā kā citu autoru darbos, kuros šajā apgabalā novērots zemākais berzes koeficients. Pieliktajam svaram ir lielāka ietekme uz rezultātiem pie gaisa temperatūrām, kuras tuvas ledus kušanas robežai, liekot domāt, ka šajā situācijā paraugiem ir vieglāk pārvarēt bremzējošos spēkus nekā sausās berzes gadījumā. Turpmākajos pētījumos nepieciešams pārbaudīt iegūtās likumsakarības, izmantojot garāku slīpo plakni, lielākus svarus un attīstot lielākus ātrumus, lai redzētu vai laboratorijas rezultāti sakrīt ar reālām dzīves situācijām.

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