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A study of convergence of ξ approximations transform by region depended given as determined by $\sigma_n(t)$ Functions on entire complex plane

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Abstract: In this study, the convergence behavior of the ξ approximants transform given as determined by $\sigma_n(t)$ functions for the exponential operators is investigated on the entire complex plain. An algorithm is developed to observe how to transform a initial region on the complex plane defined by ξ approximants.

Keywords: LIE OPERATORS, COMPLEX RECURSIVE FUNCTIONS, EVALUATION OPERATORS

1. Introduction

In this study, the convergence behavior of the ξ approximants transform given as determined by $\sigma_n(t)$ functions for the exponential operators is investigated on the entire complex plain and an algorithm is developed to observe how to transform a initial region on the complex plane defined by ξ approximants.

System with n degrees of freedom will be characterized by $x_1, x_2, \dots, x_n$ complex variables, which are considered as the coordinates of a point or components of a vector in an n-dimensional complex vector space.

$\{x_1(t), x_2(t), \dots, x_n(t)\}$: System

$x_1, x_2, \dots, x_n$: Phase space vector components in this system.

Hence $Q(t_f, t_i)$ global evolution operator is defined as

$$x(t_f) = Q(t_f, t_i).x(t_i)$$

where t_i and t_f denote the initial and final states respectively. If factorization of evolution operators is considered as a sequence of rather simple global evolution operators then the evolution operator can be written as follows

$$Q(t_f, t_i) = e^{(t_f - t_i)S}$$

where S is defined through

$$S = \sum_{j=1}^N f_j(x_1, x_2, \dots, x_N) \frac{\partial}{\partial x_j}$$

so Q evolution operator can be assumed to be written as

$$Q = e^{t f(x) \frac{\partial}{\partial x}} = \prod_{j=1}^{\infty} e^{\sigma_j(t) x^j \frac{\partial}{\partial x}} \quad \sigma_j(t) = t f_j$$

where $L = f(x) \frac{\partial}{\partial x}$ and

$$f(x) = \sum_{j=1}^{\infty} f_j x^j \quad |x| < \rho$$

This equation is factorization formula for the one-dimensional case.

The essential approximation is to truncate

$$Q = \prod_{j=1}^{\infty} e^{\sigma_j(t) x^j \frac{\partial}{\partial x}} \quad \sigma_j(t) = t. f_j$$

to a finite order. By this way it produces the following approximation.

$$\bar{\xi}_n(x, t) = \left\{ \prod_{j=1}^n Q^{(j)} \right\} x$$

If the infinite product representation of Q converges then the following result can be obtained:

$$\bar{\xi}(x, t) = Qx = e^{t f(x) \frac{\partial}{\partial x}} x = \lim_{n \rightarrow \infty} \bar{\xi}_n$$

A recursion relation for these approximants can be shown as follows:

$$\bar{\xi}_{n+1} = \frac{\bar{\xi}_n(x, t)}{[1 - n \sigma_{n+1}(t) \bar{\xi}_n^n(x, t)]^{\frac{1}{n}}}$$

And this is a recursion relation with an initial member evaluated as follows:

$$\bar{\xi}_1(x, t) = e^{\sigma_1(t) x \frac{\partial}{\partial x}} x = x e^{\sigma_1(t)} = x e^{f_1 t}$$

Although this is a simple recursion relation, the existence of f_1 may not be suitable for numerical purpose depending on the value of f_1 . So we can normalize ξ - approximants as follows:

$$\bar{\sigma}_{n+1} = n \sigma_{n+1} e^{n f_1 t}$$

Then the final recursion relation becomes as follows:

$$\xi_{n+1}(x, t) = \frac{\xi_n(x, t)}{(1 - \bar{\sigma}_{n+1}(t) \xi_n^n(x, t))^{\frac{1}{n}}}$$

The relation between the final and the previous approximants can be given as

$$\bar{\xi}_n(x, t) = \xi_n(x, t) x e^{f_1 t}$$

In this study the convergence of the ξ -approximant sequences in the complex plane is main issue. The above transformation of ξ_n to ξ_{n+1} can be interpreted as applying some basic elementary transformations consecutively

$$\xi_{n+1} = \frac{\xi_n}{(1 - \sigma_{n+1} \xi_n^n)^{\frac{1}{n}}}$$

Here $\sigma_n(t)$ functions are assumed to be given and the ξ -approximants' nature are determined by these $\sigma_n(t)$ functions. The main purpose of the examination of this convergence is to give important information about the convergence of finite product sequences that appears during the factorization of these sequences.

In this study an algorithm is developed to find out or observe how the above recursion relation defined via ξ -approximants transform a given initial region on the complex plane defined by ξ -approximants and a develop a computer program based on this algorithm.

A singular point taken in the domain can carry us to infinity on the ξ_{n+1} -plane as can be noticed through

$$\xi_{n+1} = \frac{\xi_n}{(1 - \sigma_{n+1} \xi_n^n)^{\frac{1}{n}}}$$

Therefore one can obtain a singularity free initial region on ξ_n - plane by determining the locations of these singularities and discarding them from the domain.

In this study, the original contribution is the separation of the recursion relation between two consecutive ξ -approximants into basic simple consecutive transformations.

The other contributions are the construction of an algorithm that evaluates the region variations through the consecutive transformations and to develop a computer program to execute this

algorithm. The computer program is written in C++ language and Mathematica is used for graphs.

2. Examining of The Convergence

If we assume that the functions represented by $\sigma_n(t)$ are given quantities, we need to trace how the ξ -approximants behave on the complex number plane.

$$\xi_{n+1} = \frac{\xi_n}{(1 - \sigma_{n+1} \xi_n^{\frac{1}{n}})}$$

Although it is important that the functions $\sigma_n(t)$ depend on t , it will be assumed that the $\sigma_n(t)$ take into for a certain value of t , that is, we will deal with pointwise convergence.

Let us consider $\sigma_{n+1}(t)$ function sequences as constant, but convergent or non-convergent sequences.

For $|\xi_1|=R$ circle, we obtain iterative functions as below.

$$\begin{aligned}\xi_1 &= \xi_1 \\ \xi_2 &= \frac{\xi_1}{1 - \sigma_2 \xi_1} \\ \xi_3 &= \frac{\xi_2}{(1 - \sigma_3 \xi_2^2)^{\frac{1}{2}}} \\ \xi_4 &= \frac{\xi_3}{(1 - \sigma_4 \xi_3^2)^{\frac{1}{3}}} \\ &\vdots\end{aligned}$$

If the sequences $\sigma_1, \sigma_2, \sigma_3, \dots, \sigma_n$ are taken as constant arrays such as $1, n, \frac{1}{n}, \frac{1}{n^2} \dots$ ξ -approximants will show different behavior.

It is impossible to solve the ξ_{n+1} sequences by analytically except by taking $n = 1$, for $|z| = R$ and $\sigma = \text{const}$.

However, it may be possible to examine the graphs found by some operations on functions.

The graphs in Figure 1 show four consecutive transformations, taking the $\sigma_n(t) = n$ sequence of the $|\xi_1| = 1$ unit circle in the complex number plane.

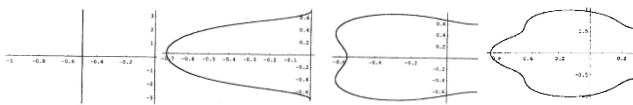


Figure 1

Here it can be easily seen that the transformation obtained with ξ_2 transforms into the line $u = -\frac{1}{2}$, and the inside of the unit circle transforms into the region to the right of the line $u = -\frac{1}{2}$.

In the next step, the line $u = -\frac{1}{2}$ turn into a parabola with its peak around $x = -0.7$ and its arms extending to $x = +\infty$.

The region to the right of $u = -\frac{1}{2}$ has turned inside of the parabola. The arms of the parabola cut the y-axis around ± 0.7 .

In the next transformations, generally appear look likes these parabolas.

However, they are not smooth due to error congestion.

The graphs in Figure 2 show four consecutive transformations, taking the $\sigma_n(t) = 1$ sequence of the $|\xi_1| = 1$ unit circle in the complex number plane.

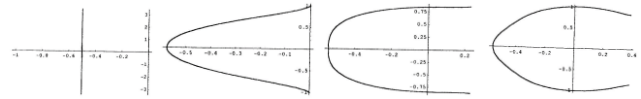


Figure 2

The graphs in Figure 3 show four consecutive transformations, taking the $\sigma_n(t) = \frac{1}{n}$ sequence of the $|\xi_1| = 1$ unit circle in the complex number plane.

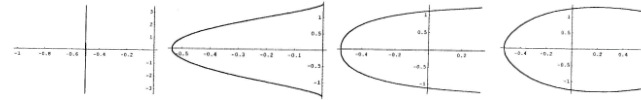


Figure 3

3. Conclusion

In this study has shown for the $\sigma_n(t)$ sequences that the equivalent in the ξ_n -plane of a circular region without a singularity for the ξ_1 -plane will remain without singularity in the ξ_n series, regardless of n and time.

Here all the transformations remain open at infinity because they are the branch points of systems.

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Modeling of agent-based cyber-physical systems using goal-oriented approach

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Abstract: Cyber-physical systems (CPS) integrate computing, networking and physical dynamics and are characterized by a high degree of heterogeneity and parallelism, with high dimensionality and complexity, including a variety of decision-making capabilities and control logic. Modeling and simulation of cyber-physical systems are considered important stages in the design, development and operation of CPS and their components. The main aim of the paper is to describe and analyze the evolution of agent based approach in the field of CPS and to define the basic requirements to the agent based systems regarding CPS. Based on O-MaSE methodology a software process model for agent based development of CPS is proposed. The approach includes the creation of 10 models reflecting various aspects and functionality of the CPS. The suggested approach is analyzed in terms of meeting the basic requirements for agent-based systems, imposed by the peculiarities of cyber-physical systems and fundamental requirements for their introducing, such as flexibility/changeability, reliability, reconfigurability, adaptability/agility and dependability.

Keywords: MODELING, CYBER-PHYSICAL SYSTEMS, AGENT BASED SYSTEMS, GOAL-ORIENTED APPROACH, INDUSTRY-4.0

1. Introduction

The backbone of Forth Industrial revolution are the Cyber-Physical Production Systems (CPPS), which are considered to be new types of systems that expand the capabilities of physical world through computing, communications and control, and upgrade the electronic automation. Cyber-Physical Systems (CPS) are physical and engineered systems whose operations are monitored, coordinated, controlled and integrated by a computing and communication core [1]. They are unique in that the components can be distributed both spatially and temporally, and include complex networks of feedback controllers and real time communication. The impact of CPS is revolutionary and pervasive as stated by CPS Public Working Group at NIST (National Institute of Standards and Technology) [2] as the development of these systems is related to the emergence of autonomous vehicles, smart grids, smart cities and homes, robots, smart medical devices, telemedicine, Internet of Things (IoT) etc. Still, however the science is owed to CPS, the lack of theoretical foundation and methodologies creates barriers that may hamper the adoption, commercialization, and market success of new CPS applications [3]. The fundamental requirements for introducing CPS in industry are specified by [4] as follows:

- Flexibility/changeability;
- Reliability;
- Reconfigurability;
- Adaptability/agility;
- Dependability.

Cyber-physical systems (CPS) are an integration of computational and physical processes. They use embedded computers and networks for the purpose of monitoring and controlling physical processes based on feedback [5]. Through cyber-physical systems, the physical world connects to the virtual world to form the "Internet of Things, Data, and Services." One of the most promising applications of CPSs is cyber-physical production systems. Modern CPSs are characterized by high dimensionality and complexity, including a variety of decision-making capabilities and control logic. The degree of communication of these systems with physical processes, based on algorithms with increased efficiency and robustness, is also increasing. The amount of logic-based program code significantly exceeds traditional control algorithms.

Modelling and simulation of cyber-physical systems and their components (embedded, mechatronic, etc.) is considered as an important stage in the design, development and operation of CPS and their components. One of the most successful approaches used for CPS design is model-based design [6] and model-driven

development [7], where models play a significant role in the design process. The digital twins that are increasingly important and culminating in the field of CPS involve the creation of digital simulation models of physical and technical objects that are dynamic, updated and changed according to the life cycle of the physical object [8]. Such dynamically updated models are able to continuously receive new information about the measurements from sensors on the physical part of the CPS, from sensors on the control devices and from the environment. Systems of a higher hierarchical level summarize the newly obtained and past data and change the parameters of the model [9]. The dynamically updated CPS model is essentially its digital twin.

CPS may be modeled as agent based systems, defined as "a loosely coupled network of problem solvers (agents) that work together to solve problems that are beyond the individual capabilities or knowledge of each problem solver" [10]. The agent community has considerable interest in developing methods and techniques for specifying, modelling, implementing and verifying of agent based CPS for different applications domains, but the adoption of agent technology in industrial applications is critical in respect to real time constraints and this implies the use of technologies for real-time control and so far no standardized methodology has been recognized.

The main aim of the paper is to present the current state of the art in the use of agent based systems for development of CPS and to analyse the main requirements to them in respect to CPS. The suggested goal oriented approach based on O-MaSE methodology [11, 12] and combined with the ontology for domain and semantic service descriptions. The approach is supported by the development environment agentTool III (aT3) in Eclipse is presented and analysed regarding the fulfilling of the defined basic requirements [13].

The paper is presented in three parts. After the Introduction, the second part of the paper discusses the basic principles of agent based systems and their use in the domain of industry and CPS. The third part of the paper presents a goal oriented agent based approach and analyzes its application for development of CPS according the selected requirements. Finally, some conclusions representing the analysis results are made.

2. Overview of modeling agent based CPS

2.1. Basic principles of agent based CPS

The concept of CPS is closely related to agent-based systems due to their core properties such as: autonomy, society, reactivity, proactivity and mobility. Different methodologies and methods are used in order to guarantee the useful features of agents in various

applications areas of CPS, such as modelling, monitoring, control, diagnostics etc. CPS may be modelled as agent-based system, which may be defined as “a loosely coupled network of problem solvers (agents) that work together to solve problems that are beyond the individual capabilities or knowledge of each problem solver” [14]. Jennings and Wooldridge [15] have defined an agent as “a computer system situated in some environment and capable of autonomous action in this environment, in order to meet its design objectives”. Software agents may be seen as building blocks for virtual environments which augment the reality. The main agent properties and characteristics are defined and discussed in [16] and are: autonomy, socialability (interactivity), reactivity, proactiveness and mobility. The agent community has considerable interest in developing methods and techniques for specifying, modelling, implementing and verifying of agent-based CPS in the different applications domains, but so far no standardized methodology has been recognized.

2.2. Methodologies for modeling of agent based CPS

There are several established methodologies for developing and analyzing agent-based systems. An analysis in [17] shows that some of the oldest methodologies, such as GAIA and MESSAGE, have a limited scope, and the fastest growing methodologies over the years are Tropos, Prometheus and INGENIAS. The largest number of life cycle phases is supported by the PASSI, Tropos, Prometheus, INGENIAS, ADELFE and MaSE (O-MaSE). The main features of methodologies are defined vocabulary and notations, procedures for executing tasks, guidelines for checking the products, methods and tools. Unfortunately, recent developments in the field, such as ASEME, OperA, GorMAS, ForMAAD, and DSML4MAS, are only methods that implement particular aspects of a methodology.

An analysis of above methodologies and methods shows that their use in industrial practice is limited. The main reason for this is the unsatisfactory development of the implementation, testing, installation and maintenance phases. There is still no methodology that is complete, mature and highly effective. The positive trends in the development of agent-based methodologies are: increasing use of meta-models and transformation in the definition of vocabularies and notations, use of methods for specification, encouragement of Method Engineering practices, and use of tools with open code as for example Eclipse Process Framework Composer. One other serious problems of using agent-based methodologies is the achievement of interoperability. Therefore, many studies are related to their combination with the service-oriented architecture and the definition of service-oriented agents, as suggested by Leitão et al. [18], or by the replacement of Agent Communication Language (ACL) with semantic agents [19, 20]. An important conclusion to be drawn from the analysis of the approaches is that the results are more successful when the agent based approach is combined with other approaches, methods and tools. Five key requirements to agent based systems are identify in respect to CPPS [21]:

- Application independence of MAS and its protocols and messages (R1.1);
- Level independence meaning that all levels of automation pyramid according ISA 95 are available (R1.2);
- Platform independent implementation (R1.3);
- Robustness against errors and unforeseen problems (R1.4);
- Decentralization means that MAS have to deal with temporary network connection loss and critical data (R1.5).

The O-MaSE methodology [11, 12] is an established methodology for agent-based system development that most closely matches the recent positive trends in the development of methodologies, covers the major phases of the software development lifecycle - from the requirements definition phase to the implementation and automatic code generation. The methodology can be refined based on existing meta-models in order to extend the modelling language and define new processes and notations. The next part of the paper presents an approach applying

this methodology for the purposes of developing cyber-physical production systems and an in depth analysis of the goal oriented approach in terms of meeting the basic requirements for agent-based systems, imposed by the peculiarities of cyber-physical systems and fundamental requirements for their introducing, such as flexibility/changeability, reliability, reconfigurability, adaptability/agility and dependability.

3. Analysis of goal oriented approach for modeling of agent based CPS

3.1. Description of the goal oriented approach

In order to fulfil the basic requirements to the CPS, the software infrastructure of the system is necessary to be distributed, enabling self-organization of devices and their software components. CPSs are much more complicated than traditional computing systems and characteristics such as adaptability, flexibility, interoperability and modularity are more important. Furthermore, these systems must provide common improvements such as service discovery, self-organization, rich knowledge representations and context-awareness.

The suggested model driven approach supporting the fulfilment of above mentioned requirements using the O-MaSE agent-based methodology, comprising the whole development life cycle of CPS, starting with computing independent meta-model (CIMM) to the deployment phase. The approach is illustrated in Fig.1 using 4 layers: one CIM layer, two PIM (Platform Independent Model) layers and one PSM (Platform Specific Model) layer. Four principles as architecture cornerstones are chosen:

- Model-driven principle, supporting the platform independent and model based domain engineering;
- Service model;
- Meta-ontology for description the domain of loosely coupled, reusable, composable agents;
- aT3 meta-model [13] - platform-independent model that specifies agent-based CPS in a technology independent manner, based on the O-MaSE process framework [11].

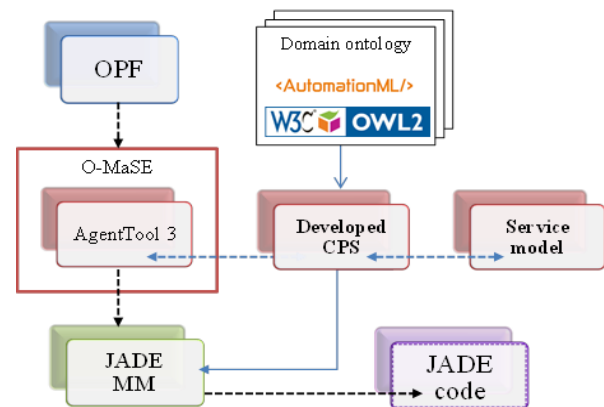


Fig.1: Illustration of the suggested approach

The platform-independent meta-model for service-oriented architecture covers four important aspects: information, services, processes and quality of service. For example the services aspect includes the services, which are represented as collaborations specifying pattern of interactions between participating roles.

The O-MaSE methodology framework is shown in Fig.2 and is based on O-MaSE meta-model and SPEM meta-model, defining the product and methodology related concepts, respectively. O-MaSE process framework is in form of meta-model, method fragments, and guidelines, based on the Eclipse Process Framework (EPF) meta-model at the CIM level of model hierarchy. EPF meta-model is a generic process meta-model defining different types of method fragments and consists of Stages, Work Units (Activities, Tasks, and Techniques), Producers, Work Products, and Languages. The

O-MaSE meta-model is based on an organizational and goal oriented approach and defines the basic concepts and relationships used for definition of agent-based systems, such as goal, role, agent, capability, protocol, policy, etc.

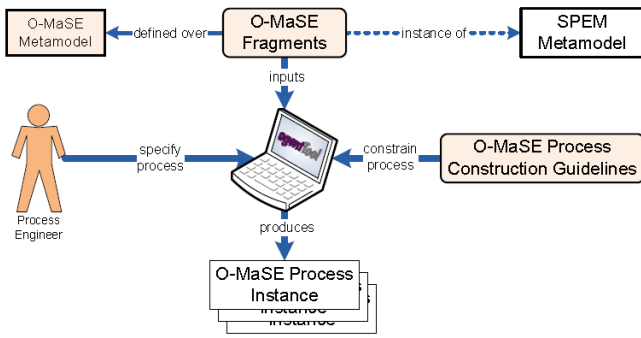


Fig.2: O-MaSE methodology framework [12]

The development environment „AgentTools III“, also known as aT3, supports the development of agent-based CPS following the O-MaSE methodology. The tool support the software processes at PIM layer, consisting of four components: graphical editor, process editor, verification framework, and code generation facility, providing abstractions that are tailored to the specific problem domain of agent-based development. The structure of aT3 is divided into several viewpoints each focusing on a particular aspects of agent-based systems. This separation allows extending the core of aT3 in order to reflect additional application-specific requirements. The tool is built on the Eclipse platform as plug-in and supports an Iterative, Incremental, Parallel Life Cycle model with 4 basic life cycle phases: requirements engineering, analysis, design, and implementation. It also provides the ability to compose and maintain customized O-MaSE complaint processes. Additionally, aT3 provides a verification framework, which helps designers to maintain consistency between their O-MaSE models. Currently, agentTool III provides the following 10 diagramming plug-ins: Goal Diagram, Organization Diagram, Role Diagram, Agent Diagram, Capability Diagram, Domain Diagram, Plan Diagram, Protocol Diagram, Policy Set and Value Goal Model Diagram.

With the proposed approach it is possible to design an agent-based CPS specifying high level concepts in a platform-independent agent model (focusing on the domain model), and later automatically transform it for different implementation models, bridging the gap between design and implementation phases. The use of two layers of PIM models enables for horizontal transformation between the models of the second layer and the use of "foreign" environments for performance.

3.2. Short description of software process model

The development of agent-based CPS follows the software process model (development life cycle model), shown in Fig.3 and includes 4 phases (requirements definition, analysis, design and implementation). It is supported by the following models:

- **Goal model:** This model is the starting point to the development process and is used in the phase of requirements definition and modelling of requirements to the system. The goal diagram is based on tree structure and AND/OR relationships for defining the selected functional and non-functional requirements to the project. Trigger relationships may also be used for defining dynamical appearing goals. The main goals are refined by the definition of sub-goals based on attribute-precede-trigger analysis. Refining goals may include specifying precedence constraints between goals, determining events causing specific goals, or specifying parameters that characterize goal states.

- **Domain model:** It captures object types, relationships, and behaviours defining the domain in which agents are sensing and acting. The suggested approach extends the O-MaSE replacing

the simple domain model with domain ontology based on ISA 95 standard.

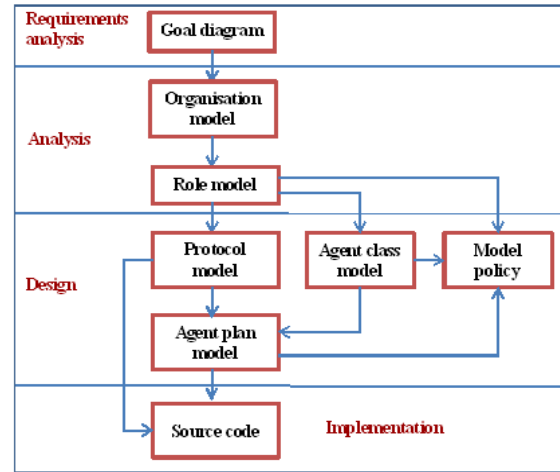


Fig.3: Suggested software process model

- **Organization model:** This model is a static model and is used at the analysis phase to represents the relationships of the system to external users through interfaces, defined as protocols. Fig.4 presents a typical organization model of a CPS, which includes 4 actors "Operator", "Cloud" (data is stored in the cloud), "Other cyber-physical system", "ERP system". The organization requires analysis and receives the results from the actor "Cloud". The "Other Cyber-physical System" actor requires and sends data to the organization as well as the organization to it. An "operator" can select a mode and receive reports from the organization. An ERP system can send a schedule and receive data about the cyber-physical system from the organization.

- **Role Model:** The Role Model defines the type of roles in the organization and the goals they are designed to be achieved. This model supports the creation of all models at the design phase, such as protocol diagram, agent class model and model policy. The role diagram is similar to the UML class diagram.

- **Capability model:** This model describes the internal structure of the capabilities possessed by the agents and is described as an action or plan. The plan is presented through a state machine.

- **Agent model:** The agent class model defines the agents used in the project and their relationships with actors, organizations, roles, capabilities and protocols. The agent class can be considered as a template of the type of agents used in the system, which is characterized by certain capabilities and/or playing certain roles. The agent classes differ from the object-oriented, because they are defined through roles, instead of using attributes and methods.

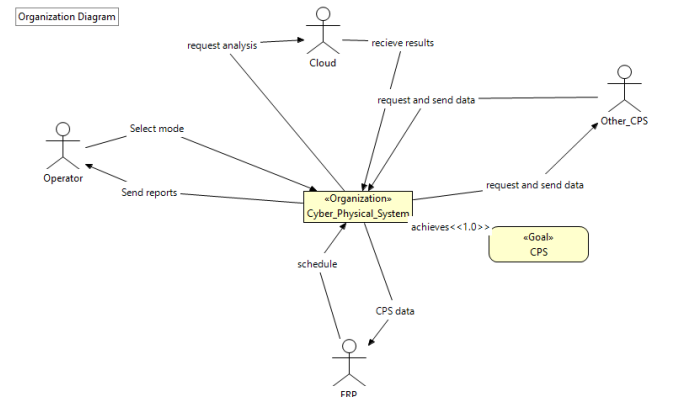


Fig.4: An example of Organization model

- **Protocol model:** The interactions in the system between roles and actors are described as sequences of messages or actions through the Protocol model, which look like an UML Sequence diagram. Two types of protocols are used – internal protocols

defining the interactions between actions within an organization and external – between organization and external actors.

- *Agent plan model*: This model uses Finite State Automata to describe the behaviour of agents/roles in achieving certain goal.

- *Policy model*: This model is very important model that formalizes the system's policies with a view to verifying it, by composing quantifiers using different patterns such as absence, existence, response, universality etc., and scopes as after, before, between etc. in order to define predicates, which must be verified. It may be used to specify liveness and safety properties of the system being designed

3.3. Analysis of the suggested approach

The suggested approach uses common meta-model that supports the adaptability of the developed agent based system. It integrates the agent based approach with representing the domain knowledge through ontology and in this way supports the reconfigurability of the system. The use of formal models in the different phases of development life cycle such as capability models, agent plan model and policy model, allows performing the verification of various aspects of development, which leads to a significant increase in its dependability and reliability.

4. CONCLUSIONS

Achieving the basic requirements to the cyber-physical systems such as flexibility, reliability, reconfigurability, adaptability and dependability requires the use of new, advanced methods in their development life cycle. The suggested approach uses an extension of O-MaSE methodology combined with ontology for domain and semantic service descriptions in order to meet the above mentioned requirements. The models used by the approach support its industrial application, as they meet the requirements for independence from the application, the level of management in the pyramid of automation, platform independence, robustness to errors and unpredictable problems and decentralization.

Some of the main reasons to choose the O-MaSE methodology and process framework, and the agentTool III meta-model are the possibilities to customize and extend the development process and to fully fill the gap between design and implementation phases, generating the code of JADE based application.

Important advantage of the proposed approach resulting from the use of meta-models and models and their formalization is the ability to verify and validate the models, as well as to increase the security and safety of the applications. The use of organization-based engineering and goal-driven development are successful steps to achieving intelligent agent – based CPS.

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Simulation of the main components of a nuclear reactor under load, made of ultrafine-grained steel AISI-321 in the normal and irradiated state

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Abstract: The creation and calculation of computer models of various products under load with the properties of UFG materials in the normal and irradiated state was performed. To model the UFG properties of non-irradiated AISI-321 steel, hardening curves were constructed based on the Hall-Petch equation for the base state of the material at a grain size of 1500 nm and for two UFG states (with grain sizes of 700 and 200 nm). To simulate the properties of irradiated AISI-321 steel, plastometric tests were performed using uniaxial compression of cylindrical samples at constant values of the strain rate of 1 s^{-1} and the temperature of 20°C on the "Gleeble 3800" plastometric unit. Fast neutron fluence with the following values was selected as a variable parameter: $0.5 \cdot 10^{18} \text{ n/cm}^2$, $1 \cdot 10^{18} \text{ n/cm}^2$, $0.5 \cdot 10^{19} \text{ n/cm}^2$, $1 \cdot 10^{19} \text{ n/cm}^2$. The maximum operating pressure of 340 MPa was used as a static load. The simulation results showed that for both parts, the use of the material in the UFG state is the most appropriate solution.

Keywords: FEM, UFG STRUCTURE, IRRADIATION, STRESS

1. Introduction

The most important components of a nuclear reactor are the elements directly in contact with the nuclear fuel tablets: fuel assembly and fuel element.

The body of the fuel assembly is a metal structure (figure 1) containing fissionable substances and intended for generating thermal energy in a nuclear reactor by performing a controlled nuclear reaction. Usually it is a tetrahedral (PWR) or hexahedral (VVER) beam of fuel rods with a length of 2.5—3.5 m (which approximately corresponds to the height of the core) and a diameter of 30-40 cm, made of stainless steel or a zirconium alloy (to reduce neutron absorption) [1].



Figure 1 - Typical design of fuel assembly

The body of the fuel assembly has a total length of 3500 mm, there are three characteristic sections that differ not only in shape, but also in purpose. The head part is a body of rotation, the upper section of which has a conical shape, and the lower section has a cylindrical shape. It is designed for loading fuel elements, as well as fixing fuel assemblies in the overall design of the reactor. The wall thickness in this zone varies from 4 to 7 mm. The bottom part is also a cylindrical body of rotation. It is designed for loading fuel elements, as well as fixing fuel assemblies in the overall reactor structure by means of a threaded connection. The wall thickness in this zone is 4 mm. The longest central part with a length of more than 2500 mm has a hexagonal cross-section with a "turnkey" size of 96 mm and is intended for direct maintenance of fuel elements in the amount of 37 pieces. The wall thickness in this zone is 4 mm.

The geometry of the fuel element is a cylindrical body with a cavity into which uranium oxide tablets are loaded [1]. There are also three zones – head, central and bottom. But, unlike the hull, all these zones have a cylindrical shape. Wall thickness in all zones of the fuel elements is 0.45 mm.

2. Creation of models of UFG-materials

To create a model of AISI-321 steel in an ultrafine-grained state, it is necessary to put the values of mechanical characteristics corresponding to this state in the material database. The key parameter for this is the yield strength of the material, i.e. the mechanical characteristic of the material that characterizes the stress at which the deformations continue to grow without increasing the load. At room temperature, the yield strength is 270 MPa [2].

However, this value characterizes AISI-321 steel in the pre-deformation state, without any level of hardening. To determine the yield strength values for different grain size values, it is recommended to use the Hall-Petch ratio [3-4], which is the following relationship:

$$\sigma_Y = \sigma_0 + k d^{-1/2}, \quad (1)$$

where σ_Y – desired yield strength value, MPa;

σ_0 – stress impeding the dislocations movement, MPa;

k – constant, depending on the properties of a particular material;

d – grain size, microns.

In the course of experimental studies, a grain size range of 200–700 nm was obtained. Taking into account that when modeling properties, it is necessary to assume a uniform initial distribution of properties, we will set the limits of this range as the values used, i.e. we will create rheological models of AISI-321 steel with a grain size of 700 nm and 200 nm. For the initial grain size, we take the value of 1500 nm, corresponding to the yield strength of 270 MPa, according to equation (1). In [5], extensive studies of the Hall-Petch effect were carried out in relation to the two most used grades of austenitic stainless steels – AISI-316 and AISI-321. As a result, the following values were obtained: $\sigma_0 = 150 \text{ MPa}$; $k = 420$. As a result, the following values of the yield strength were obtained:

- $\sigma_Y = 652 \text{ MPa}$ (for a grain size of 700 nm);
- $\sigma_Y = 1089 \text{ MPa}$ (for a grain size of 200 nm).

In addition, the second important characteristic required for creating a material rheology is the YS / TS parameter, i.e. the ratio of yield strength to tensile strength. This ratio is not characterized by a linear relationship, but constantly changes depending on the level of deformation and processing conditions of the material. This parameter characterizes the section of the hardening curve between the yield point and the point of failure of the sample. In [12], YS / TS values for AISI-321 steel are presented, as well as data on elongation, on the basis of which the corresponding strength limit values were obtained:

- $\sigma_{TS} = 986 \text{ MPa}$ (for a grain size of 700 nm);
- $\sigma_{TS} = 1194 \text{ MPa}$ (for a grain size of 200 nm).
- $\delta = 38 \%$ (for a grain size of 700 nm);
- $\delta = 22 \%$ (for a grain size of 200 nm).

After setting these values on the graph as points and processing with the spline function [6], the AISI-321 steel hardening curves were obtained (figure 2a).

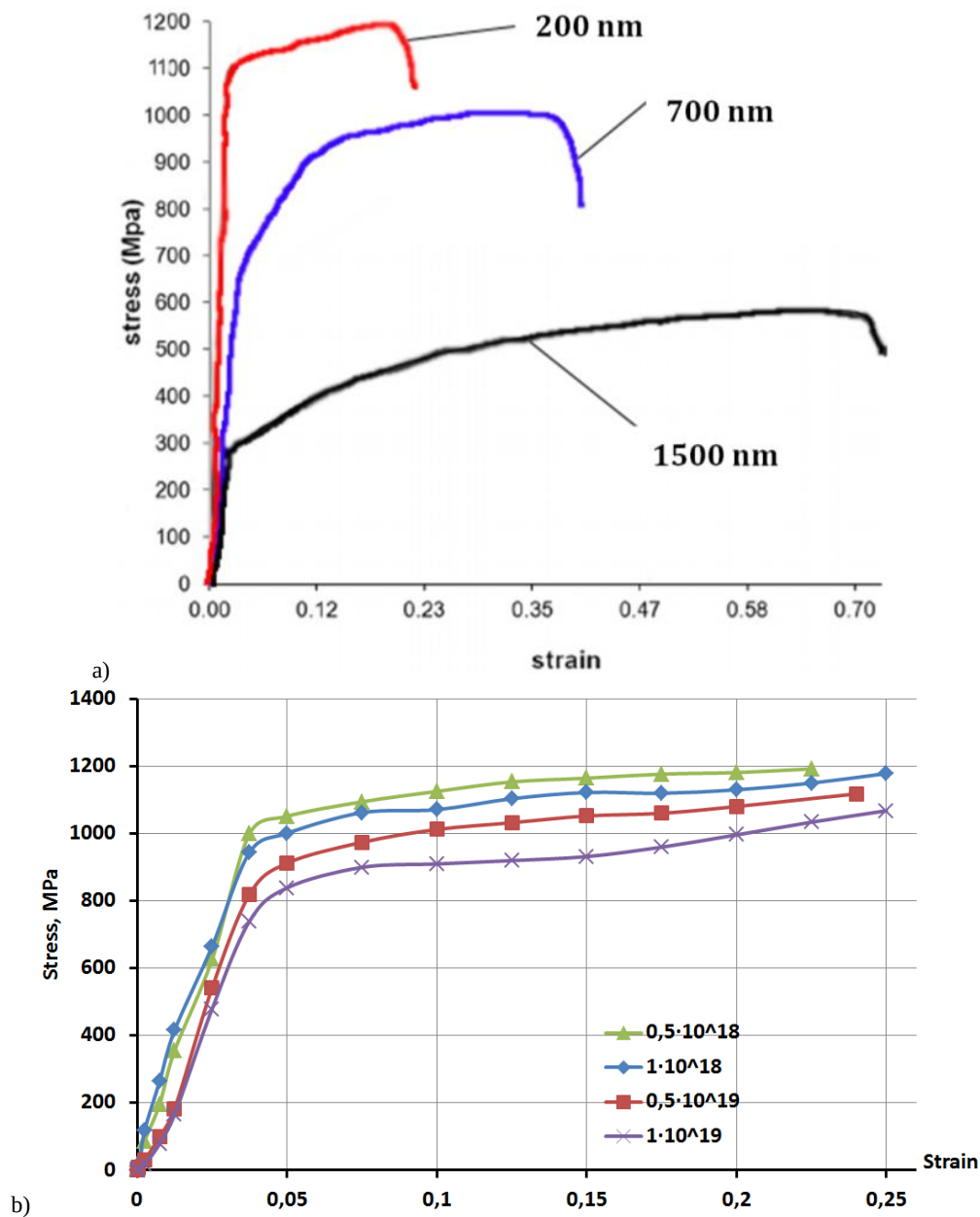


Figure 2 - AISI-321 steel hardening curves for the UFG state

When creating rheological models of irradiated material in the UFG state, the previously discussed method cannot be used. After irradiation, the metal structure is negatively affected by the fast neutron flux. As a result, a partial violation of the crystal lattice occurs at the micro level, which leads to a decrease in mechanical properties. Since it is impossible to predict the level of mechanical properties of such a material using the Hall-Petch equation due to the lack of uniformity of the structure after irradiation, the only possible way to obtain mechanical characteristics here is to conduct plastometric studies.

Plastometric tests were performed using uniaxial compression of cylindrical samples at constant values of the strain rate of 1 s^{-1} and a temperature of 20°C . As a variable parameter, the fast neutron fluence was chosen with the following values: $0.5 \cdot 10^{18} \text{ n/cm}^2$, $1 \cdot 10^{18} \text{ n/cm}^2$, $0.5 \cdot 10^{19} \text{ n/cm}^2$, $1 \cdot 10^{19} \text{ n/cm}^2$. The tests were carried out under continuous loading on a Gleeble 3800 plastometric unit using Pocket Jaw module. Based on the test results, graphs of stress-strain flow curves were obtained (figure 2b). The results show that with an increase in the value of fast neutron fluence from $0.5 \cdot 10^{18} \text{ n/cm}^2$ to $1 \cdot 10^{19} \text{ n/cm}^2$, the deformation resistance decreases by about $\sim 20\%$, which allows us to conclude that the irradiation has a negligible effect on the properties of AISI-321 steel in UFG state. It should be noted that the deformation resistance of a sample with a

maximum radiation dose of $1 \cdot 10^{19} \text{ n/cm}^2$ is higher than the properties of a homogeneous UFG material with a grain size of 700 nm. This fact allows us to conclude that, despite the known data on the significant negative impact of radiation on the structure of metals in the usual coarse-grained state, when using materials in the UFG state, the effect of radiation on the structure is significantly reduced.

3. Results and discussion

When determining the static load value, the value of 340 MPa was set as the maximum pressure in the core, according to the technical characteristics [1]. The main area of impact of the load on both parts is the central part, while the head and bottom parts serve as retainers. In accordance with this principle, the head and bottom parts were fixed in space on all three axes. After calculating the static load of the fuel Assembly housing, the following results were obtained (figure 3). When analyzing all three models of materials, a similar distribution of stress along the length of the central part of the body of the fuel assembly was noted. Despite the given uniform pressure distribution, the nature of the stress action along the length is uneven and shifted towards the head part.

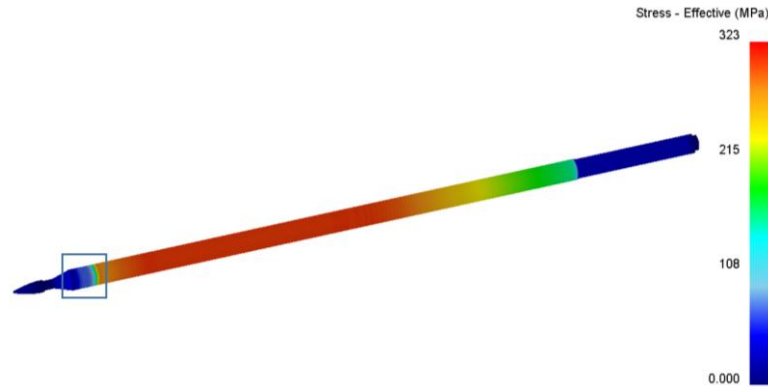


Figure 3 - Results of calculating the static load of the fuel assembly with a grain size of 1500 nm

Also here, in the area of the junction of the head and central part (in figure 3 this zone is highlighted by a frame), the effect of residual stresses is traced. This phenomenon is a consequence of the design features of the fuel assembly - the head and bottom parts have different lengths, as a result of which different levels of elastic deformation occur in them under static load. The maximum stress value recorded in this model is 274 MPa. According to this value, you can determine the safety margin in the most loaded areas under the specified operating conditions: 340 MPa / 274 MPa = 1.24.

For the other two models, the following results were obtained: stress in the model with a grain size of 700 nm – 238 MPa; stress in the model with a grain size of 200 nm – 186 MPa; safety margin in the model with a grain size of 700 nm → 340 MPa / 238 MPa = 1.43; safety margin in the model with a grain size of 200 nm → 340 MPa / 186 MPa = 1.83. Thus, when using AISI-321 steel in the UFG state as the fuel assembly material, it is possible to increase the safety margin by 15–47%, depending on the resulting grain size.

After calculating the static load of the fuel element, the following results were obtained (figure 4).

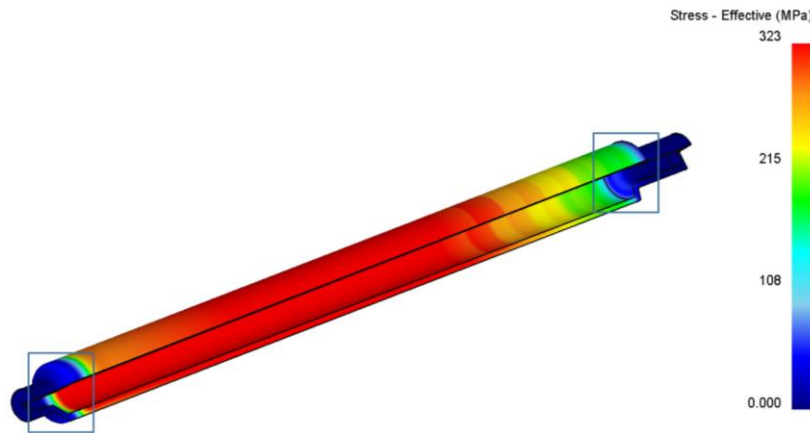


Figure 4 - Results of calculating the static load of a fuel element with a grain size of 1500 nm

The nature of the stress distribution here is similar to the distribution on the fuel assembly – there is an uneven spread along the length of the central part, with a shift to the head part. However, in contrast to the previously discussed case, in this part, under static load, there are already two centers of action of residual stresses-in the areas of the junction of the head and bottom parts with the central one (in figure 4, these zones are highlighted by frames). The presence of such zones at both ends of the central part is a consequence of the fact that the length of the head and bottom parts in the design of the fuel element is not so different as in the case of the fuel assembly.

The maximum values of stresses recorded in these models are as follows: the stress in the model with a grain size of 1500 nm – 313 MPa; the stress in the model with a grain size of 700 nm - 269 MPa; the stress in the model with a grain size of 200 nm – 224 MPa. According to these values, it is possible to determine the safety margin in the most loaded areas for all three materials under the specified operating conditions: the safety margin in the model with a grain size of 1500 nm → 340 MPa / 313 MPa = 1.08; the safety margin in the model with a grain size of 700 nm → 340 MPa / 269 MPa = 1.26; safety margin in a model with a grain size of 200 nm → 340 MPa / 224 MPa = 1.51. Thus, when using AISI-321 steel in the UFG state as the material of the body of the fuel element, it is possible to increase the safety margin by 17–40%, depending on the resulting grain size. At the same time, it is necessary to note a decrease in the overall level of safety margin at a constant level of

static load. This phenomenon is directly related to the design features of both parts. In particular, this occurs due to the different wall thickness in the central part – if the wall thickness in the fuel assembly is 4 mm, then in the fuel element it is almost an order of magnitude less – 0.45 mm.

When modeling the behavior of the studied parts made of AISI-321 irradiated UFG steel under static load, the same criteria were used that would be accepted for modeling homogeneous materials. After calculating the static load of the fuel assembly, the following results were obtained:

Maximum stress values:

- in the model after irradiation at $0.5 \cdot 10^{18}$ n/cm² – 192 MPa;
- in the model after irradiation at $1 \cdot 10^{18}$ n/cm² - 198 MPa;
- in the model after irradiation at $0.5 \cdot 10^{19}$ n/cm² - 209 MPa;
- in the model after irradiation at $1 \cdot 10^{19}$ n/cm² - 227 MPa.

Safety margin for all four irradiated materials under specified operating conditions:

- in the model after irradiation at $0.5 \cdot 10^{18}$ n/cm² → 340 MPa / 192 MPa = 1.77;
- in the model after irradiation at $1 \cdot 10^{18}$ n/cm² → 340 MPa / 198 MPa = 1.71;
- in the model after irradiation at $0.5 \cdot 10^{19}$ n/cm² → 340 MPa / 209 MPa = 1.62;
- in the model after irradiation at $1 \cdot 10^{19}$ n/cm² → 340 MPa / 227 MPa = 1.49.

After calculating the static load of the fuel element, the following results were obtained.

Maximum stress values:

- in the model after irradiation at $0.5 \cdot 10^{18}$ n/cm² - 233 MPa;
- in the model after irradiation at $1 \cdot 10^{18}$ n/cm² - 241 MPa;
- in the model after irradiation at $0.5 \cdot 10^{19}$ n/cm² - 249 MPa;
- in the model after irradiation at $1 \cdot 10^{19}$ n/cm² - 258 MPa.

Safety margin:

- in the model after irradiation at $0.5 \cdot 10^{18}$ n/cm² → 340 MPa / 233 MPa = 1.46;

- in the model after irradiation at $1 \cdot 10^{18}$ n/cm² → 340 MPa / 241 MPa = 1.42;

- in the model after irradiation at $0.5 \cdot 10^{19}$ n/cm² → 340 MPa / 249 MPa = 1.37;

- in the model after irradiation at $1 \cdot 10^{19}$ n/cm² → 340 MPa / 258 MPa = 1.31.

Figure 5 shows a summary diagram of the safety factor for the fuel assembly and fuel element when using conventional and irradiated variations of AISI-321 steel in UFG state.

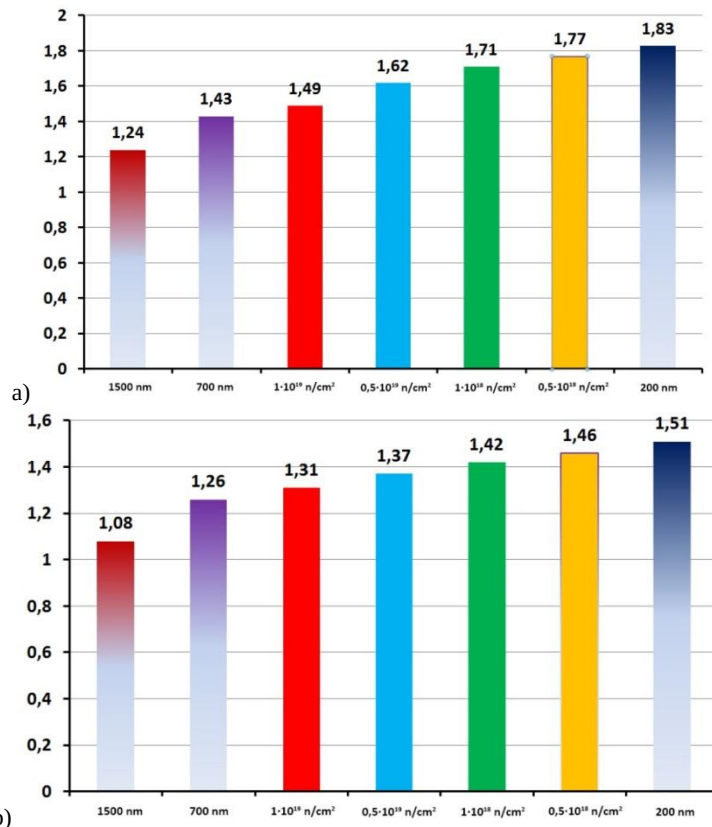


Figure 5 - Diagrams of the safety factor of the fuel assembly (a) and fuel element (b)

Thus, when using AISI-321 steel in the UFG irradiated state as the material both for fuel assembly and fuel element, the margin of safety increases with a decrease in the level of radiation dose. At the same time, it was noted that even at maximum irradiation, the margin of safety in both parts does not reach the lower limit of the UFG structure of 700 nm.

Conclusions

The creation and calculation of computer models of various products under load with the properties of UFG materials in the normal and irradiated state was carried out. As the products under consideration, the fuel assembly and the fuel element were selected as the most suitable reactor parts in terms of size. To model the properties of UFG non-irradiated AISI-321 steel, the Hall-Petch equation was used to construct hardening curves for the base state of the material at a grain size of 1500 nm and for two UFG states (with grain sizes of 700 and 200 nm). To simulate the properties of UFG irradiated AISI-321 steel, plastometric tests were performed using uniaxial compression of cylindrical samples at constant values of the strain rate of 1 s^{-1} and a temperature of 20°C on the "Gleeble 3800" plastometric unit. As a variable parameter, the fast neutron fluence was chosen with the following values: $0.5 \cdot 10^{18}$ n/cm², $1 \cdot 10^{18}$ n/cm², $0.5 \cdot 10^{19}$ n/cm², $1 \cdot 10^{19}$ n/cm². The maximum operating pressure of 340 MPa was used as a static load. The simulation results showed that for both parts, the use of material in the UFG state is the most appropriate solution, since in this case the margin of safety even

at maximum irradiation in both parts does not reach the lower limit of the UFG structure.

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Mathematical modeling of automated production systems

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Abstract: The paper theoretically substantiates and practically implements mathematical methods of modeling production systems, proves the adequacy of mathematical models and optimization methods, as well as selected rational optimization methods and created software that implements the selected methods in practice. The analysis of methods of modeling and optimization of production technological systems is performed, the most effective methods of solving these problems for discrete production are selected. The main provisions of infinite-valued logic and ordinal determinants, on which the structural-logical approach to the study of complex systems, which include production systems in instrument making, are considered.

KEY WORDS: production system, mathematical modeling, optimization, structural-logical method, the method of branches and boundaries.

1. Introduction

Development of methods for modeling and optimization of production systems is a promising scientific and technical task, which is of great importance for creating the optimal structure of the production system, which will reduce production costs without investing significantly in re-equipment, development of technological equipment [1–3].

Solving this problem involves various aspects of production, one of the main ones being the manufacturing time of the product. Along with the improvement of technological processes and material and technical base, the optimal loading of the production system equipment allows to significantly reduce the manufacturing time of products by minimizing equipment downtime. Thus, the optimization of the loading of technological equipment is an urgent problem in modern instrumentation. This problem is solved by modeling the operation of production systems [3–5].

To date, there is no single method of modeling production systems in general, i.e. those that would adequately and accurately describe the parameters of production systems of different structures, so to model a particular type of system, or at least several similar types of structures use different mathematical models [6–9].

To model the loading of technological equipment of production systems, it is proposed to apply the structural-logical method, as it can be used in production systems of various structures, namely: serial, parallel, parallel-serial, serial-parallel. In addition, this method is easily formalized and programmatically implemented [10, 11].

2. Fundamentals of structural and parametric optimization of production systems

When designing technological processes and operation of production equipment, the main set of tasks is related to the choice of the best version of the production system on a set of technical and economic indicators. These problems have several varieties, which correspond to three levels of optimization [11]:

- the first level of optimization is to choose the best technical idea or principle of operation of the projected object;
- the second - in search of the best structure or scheme within the chosen principle of action;
- the third - in determining the best values of parameters for the selected structure (scheme).

The division into three levels is conditional, and it is impossible to draw a strict line between them. The expediency of such a division is due to the need to distinguish between simpler and more complex and time-consuming tasks, which belong to different stages of technology design and at the same time differ significantly in the methods of solution.

First-level tasks are specific to the external design stages and are solved using heuristic programming approaches and methods. Modern systems of automated design of technological processes are focused on the stages of internal design. In this case, the problems of the second and third level are typical, which are called structural and parametric optimization problems, respectively.

When solving these problems, the term production technological system means a system whose purpose is to manufacture a certain number of products in a certain time, using a clearly defined amount of equipment. Strictly speaking, in this case we will describe the production system in terms of queuing theory.

Here, the system, which in connection with possible technical, economic and other applications, is considered structural, in contrast to the abstract system, which is the subject of study of general systems theory. An element of the system is an arbitrary indivisible object in this problem.

The indivisibility of an element is conditional and is caused by the desire to simplify the problem. It is possible that the transition from one task to another will require the decomposition of one element or, conversely, the combination of several elements into one. An object that does not decompose in this but may decompose in another problem is a block.

The system is a defined set of blocks (elements), combined by some set of connections to achieve a common goal. In service systems, this goal is to perform a given set of jobs. Each job consists of a number of different operations performed by the respective blocks.

The system as a whole provides a consistent passage of each job through certain blocks, a set of operations in which ensures the performance of this job. We believe that the operation is the smallest, indivisible part of the job.

In this regard, in the study of queuing systems, quantitative characteristics (parameters) of operations must be specified.

These parameters can be set by a matrix:

$$A = \|a_{ij}\|,$$

where a_{ij} is the quantitative effect of the i -th operation in the j -th job.

Values a_{ij} – can mean either the cost of time resources, or income and so on. The specific content of these values affects the formulation of problems of studying systems. The parameters a_{ij} express the quantitative characteristics of the queuing system as a whole.

The functioning of an arbitrary system is a set of rules that determines what the system must do to achieve its goal; these rules do not necessarily use the knowledge of building a system. In general, according to the level of abstraction adopted in the study of the system, its operation can be described by more or less detailed rules.

Thus, the operation of queuing systems is usually described at the level of system structure. Under the structure of an arbitrary system we understand the set of a set of blocks (elements) and a set of connections between them. The structure of the service system is usually represented by a digraph, in which the vertices denote the blocks (elements) of the system, and the arcs - the directions of movement of works from block to block in the process of their execution.

To quantify the degree of achievement by an arbitrary system of the goal set before it, various characteristics of its functioning are introduced. Each individual characteristic evaluates one side of the system, and only together they allow to assess how the system has achieved its goals.

Production systems form structures that can be serial, parallel, parallel-serial, serial-parallel, where  is the block of the production system, i.e. the machine [10].

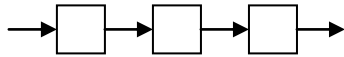


Fig. 1. An example of a serial structure of the system.

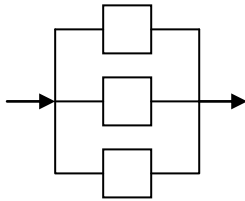


Fig. 2. An example of a parallel system structure.

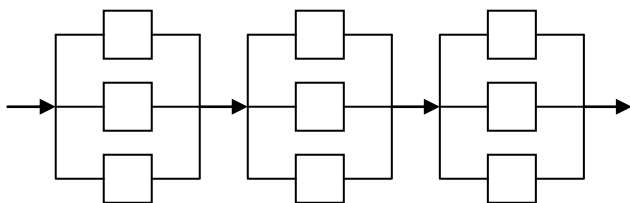


Fig. 3. An example of a parallel-serial structure of the system.

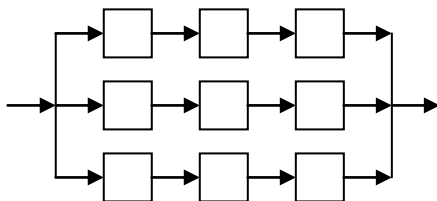


Fig. 4- Example of a serial-parallel structure of the system.

The quality of operation of any system can be assessed using certain characteristics. In this case, each performance characteristic, as a rule, evaluates a separate component of the quality of system operation, although generalizing characteristics are possible. Each class of systems has its own types of performance characteristics, although there are universal characteristics that apply to all classes of systems. Below is a short list of types of characteristics with an indication of the components of the quality of systems functioning evaluated by them. Some of these characteristics are universal, others belong to separate classes of systems.

The performance characteristics of the systems are universal. They evaluate the speed of operation of the systems. As such characteristics in service systems usually use the total execution time of the system of a fixed set of works or the number of works performed per unit time (speed of operation of the system). In other systems, performance is assessed similarly.

The boot characteristics of the systems are also universal. They assess the degree of employment of individual units and the set of units in achieving the goal of the system. As such characteristics in service systems apply a fraction of time during which the block is occupied with performance of works (average loading of the block); average for all blocks the share of employment time (average system load), etc. In other systems, the load is estimated similarly. The load is related to the performance of the systems as follows: the higher the load, the (other things being equal) the higher the performance.

The stability characteristics of the systems quantify the ability of any system to continue to function properly (albeit with poorer performance, load, etc.) in the event of block failures. To assess the

stability usually use the maximum number of blocks, with the simultaneous failure of which still retains the correct operation of the system. Stability, as well as speed and load, is a universal characteristic of the system.

The cost characteristics in the systems show the generalized costs (financial, material, energy, etc.) that are necessary for the normal functioning of the system. For service systems, such characteristics may be the total cost of the system to perform a fixed set of works; specific costs per work performed or per unit of system operation time, etc. Costs are not a universal characteristic of system operation. They relate mainly to technical, organizational, economic and production systems.

Characteristics of profit in systems estimate the generalized profit (financial, material, etc.) which appears as a result of system functioning. In service systems, these characteristics may be the total income that arises as a result of performing a fixed set of works; specific income per work performed or per unit of system operation time, etc. Profit is not a universal characteristic of systems. It applies only to organizational and economic systems.

The characteristics of the efficiency of systems are generalizing characteristics that bring together the assessments of all the above individual components of the quality of systems. The efficiency of the system shows the degree of achievement of the goal of the system. The characteristic of efficiency is often taken as the probability of achieving the goal of the system. Efficiency is a universal characteristic of the functioning of systems.

There are a number of limitations to the structure of the input data, namely:

- completely fixed structures of systems of the four above-mentioned types are taken into consideration: serial, parallel, parallel-serial and serial-parallel;
- the system has a completely fixed number of blocks, in addition, usually the number of blocks is determined by an integer;
- the system receives a clearly defined number of works, the number of which is also an integer;
- each block of the system performs a certain job for a certain time, then the matrix of time of work is the input data for calculating the parameters of the system.

The following assumptions should also be taken into account, namely:

- absolute reliability of all blocks of the service system;
- for each work is set many components of its operations, the order of execution of which is proposed by some given order ratio, and each operation is not more than one previous and one subsequent operation;
- no more than one operation can be performed simultaneously in any work;
- at any time, each block can perform no more than one operation;
- the operation started by any block is performed to the end.

To model the load of production systems it is necessary to solve a number of problems, namely: system representation, system calculation, system analysis and synthesis.

Representation of the system is the presentation of all given information about the system in a compact form, which facilitates the description of the system, as well as the formulation and solution of problems of its calculation, analysis and synthesis.

The calculation of the system is to determine the expressions or numerical values of various characteristics of the system according to the given structure of the system, the mode of its operation, the order of work entering it, and the numerical value of the parameters of its blocks.

The analysis of the system is to determine the type of dependence of various characteristics of the system on its structure, the mode of its operation, the order of execution of works in it, the values of the parameters of its blocks. The analysis allows to establish the degree of influence of these factors on the characteristics of the system. Due to this, it is possible to calculate the accuracy (stability) of the system when changing its parameters and structure.

The synthesis of the system is to find its structure and / or the order of execution of works in it on a given set of works to be performed, the values of the parameters of the blocks forming the structure, and the required values of the various characteristics of the system.

As an adequate mathematical apparatus for describing systems, infinite-valued logic is chosen - the theory of functions, the domain of which is a set of real numbers, and the main operations - disjunction, ie maximum, and conjunction, ie minimum, which are similar in properties to binary disjunctions and conjunctions. Using the structural representation of the studied system, it is possible to express any of its characteristics through similar characteristics of the blocks, using these logical operations.

This opens the way for the uniform solution of problems of calculation, analysis and synthesis. As an adequate mathematical apparatus for a compact representation of a given information about a complex system selected logical determinants - a kind of extreme numerical characteristics of rectangular matrices, expressed through the elements of the matrix by operations of infinite logic and their properties resemble ordinary determinants of square matrices.

To optimize the loading of technological equipment of the production system (ie to find the optimal order of launching parts into the system) it is advisable to use the method of branches and networks, because it is the most flexible. This method includes standard elements, namely: branching, estimation and clipping, combined into a typical optimization algorithm, consisting of a single first step and repeated the second step. The specificity for each type of system is manifested only in the form of an evaluation function.

The study of any real system is carried out on a model that is a simpler system than the original, while maintaining its essential features. Models are divided into physical and abstract, which in turn are divided into conceptual and mathematical.

Conceptual models characterize only causal relationships that are essential to describe the functioning of the system; while leaving aside the quantitative and qualitative aspects of this description.

The mathematical model is based on the conceptual and characterizes the functioning of the system in quantitative and qualitative terms.

The mathematical model of the production or technological system itself is described as follows.

There are some set of products B that need to be manufactured, and some set of units of technological equipment (machines) M , as well as workers for the manufacture of these products. Each product is characterized by its technological route, ie the sequence of passage of a certain subset M , which leads to the finished product.

The system in this case is a set of sets B and M , and its purpose – the manufacture of all products from the set B . The machines are blocks of the system, and various products - robots to be performed in this system. The technological route of the product is an ordered set of operations, which consists of the manufacturing process of this product. Each operation is performed by a separate machine (block). The effect of the operation is measured by the time required, costs, and so on.

All machines with connections between them form the structure of the system. The directional connection between the two machines shows that after performing the operation in one of them, the operation can be performed in the other.

The functioning of the system is to lay routes in its structure, in accordance with the specified technological routes of individual products, and the agreed passage of certain routes of all products until their full manufacture.

The task of structural modeling and optimization is to investigate the mathematical apparatus, which would adequately describe the structure of the production system and would allow to algorithmize the procedures for calculating the most important parameters of this system.

Usually in detailed consideration, this problem is divided into several subtasks:

a) analyze the work of production equipment for different structures and explore the features of modeling each of them;

b) choose a method of modeling the equipment of the production system, which would describe as fully as possible the parameters of the system and would allow to obtain its adequate model;

c) choose a method of optimizing the operation of equipment that would meet the given constraints and would have the best possible convergence;

The classification of systems aims, if possible, to unify the quantitative characteristics of systems, the tasks of their study and methods of solving these problems.

The classification of systems can be based on various features, so the paper considers only some of them, namely - on the structures of deterministic queuing systems.

Production systems, depending on the conditions of a particular production can have a series, parallel, parallel-series or series-parallel structure, and in the case of the intended return of the finished product to correct the defect - the structure of the feedback system. Thus, production systems can have a diverse structure.

According to the mode of operation of the units, all systems are divided into: systems with single-program and multi-program mode; static and dynamic; without downtime and with downtime of blocks. Systems with single-program (multi-program) mode of operation include those in which only one action (several actions) is performed simultaneously (for service systems - one job (several works)).

Static are systems in which during the execution of the purpose of the system (in service systems - during the execution of a given set of works) each block performs its operation not more than once, dynamic - those in which there are blocks that perform their operations for a specified time at least twice.

According to the mode of submission of works, service systems are divided into: systems with waiting and without waiting; systems with free and forced on time of receipt of works; conveyor and non-conveyor; systems with stationary and non-stationary workflow; systems with one and with several works.

Waiting systems (without waiting) include those in which the work after the previous operation is waiting for the release of the unit performing the next operation (immediately transferred to the free unit performing the next operation).

In the system with free time of work receipt all works are available already at the initial moment $t = 0$ of start of system therefore the moments of actual occurrence of works are not specified. The works are entered into the system for their execution in accordance with the presence of free blocks in it.

In systems with forced time of work, the latter appear at specified points in time, in the general case later than the moment $t = 0$ of the system startup. Here works are submitted to the system only after its appearance and in the presence of free blocks in it. Conveyor type includes systems in which the order of work is the same for all operations, and non-conveyor - other systems.

In systems with a stationary flow of work, the flow parameters do not change over time, and in systems with a non-stationary flow - change.

According to the discipline of service of works waiting in blocks, it is possible to allocate systems of service of types: 1) "came first - served first", 2) "came first - served last", 3) "came first - served average in order". 4) in ascending order of some indicator (usually the time required to complete this work in the system), 5) random service.

The scheme of the system in general is very important for its correct modeling, because often the methods of mathematical modeling are able to adequately describe only a certain, one structure and are not acceptable for modeling others.

Structural optimization of the technological systems created on the basis of the production equipment is connected with variation of their components: types and options of manufacturing of products, types, sequence and options of concentration of technological operations.

Each variant of the system is formed of elements $w_g, g = \overline{1, G}$, indicators of which $f_{\omega g}$ have different meanings for implementation: $w_g = \overline{1, W_g}$.

The set of elements w_g and the relationship between them characterize the structure of the technological system, and the task of optimization is to choose a set of combinations of elements w_g of variant s^* , which is optimal in terms of the specified technical and economic requirements: $F_i^*, i = \overline{1, I}$.

Possibilities of change of the listed components are defined by a variety of two sets and communications between them:

- production objects

$$R \subset \times \{r_j : j \in J\},$$

where $\subset$ – sign of relations;

$\times$ – sign of a Cartesian multiplication;

$r_j = \overline{1, R_j}$ – sets of numbers of production objects j -th name;

J – set of indexes for names of production objects;

– technological operations

$$V \subset \times \{v_t : t \in T\},$$

where $v_t = \overline{1, V_t}$ – set of numbers of technological operations t -th name;

T – set of name indexes for technological operations.

Thus, the structure of the technological system is a set of elements $r_i \in R, v_t \in V$ and the relationships between them.

In this case, it is convenient to consider the technological system in the form of a relation on a nonempty set of production objects and technological operations:

$$S \subset R \times V. \quad (1)$$

The elements of the set (1) are pairs of vectors r, v

$$s_l = (r, v), s_l \in S, l = \overline{1, L}.$$

Here

$$r = (r_1, \dots, r_j, \dots, r_I), j = \overline{1, J}, r_j = \overline{1, R_j}; \\ v = (v_1, \dots, v_t, \dots, v_T), t = \overline{1, T}, v(t) = \overline{1, V_t}.$$

Denote the common pair of elements $(r_j, v_t) = w_g, g = \overline{1, G}$.

Then

$$s_l = (w_1, \dots, w_g, \dots, w_G), l = \overline{1, L}, \quad (2)$$

Where $w_g = \overline{1, W_g}, g = \overline{1, G}$ – elements of the technological system;

L – the total number of variants of the technological system.

Universal methods of structural optimization take into account only the combinatorial nature of the formation of options. Therefore, only partial problems of choosing the optimal structure of technological systems can be solved on their basis.

One way to solve them is to go over and over. It involves a preliminary synthesis of options that can be obtained by forming all possible combinations of elements: $w_g = \overline{1, W_g}, g = \overline{1, G}$.

Then, for each implementation of the system, the values of the indicators are calculated $F_i, i = \overline{1, I}$, and the choice of the optimal option is carried out.

The positive side of a full search is the review of all permitted combinations, which ensures high reliability of the optimal decision.

This approach has shortcomings that impose limitations on its application.

First, the lack of mathematical models that take into account the system connections of production facilities and technological operations requires the formalization of the allowed combinations for each partial problem, which significantly increases the cost of preliminary preparation of the automated solution.

Secondly, the total number of variants of the technological system is quite significant, and the machine time required to generate them becomes unacceptable.

Third, in the case of multiple technical and economic requirements, the search for the optimal system leads to additional costs for re-research and analysis in the field of trade-offs.

An approach aimed at limiting the number of pre-synthesized variants is abbreviated random search.

However, due to the lack of mathematical models of structural optimization of the technological system, it is impossible to build targeted search procedures that predict the position of the system in the space of indicators, which reduces the reliability of incomplete search. In addition, it is not always possible to justify the condition of stopping an uncontrolled random search process.

A formalized approach to taking into account the combinatorial nature of structural optimization is achieved on the basis of discrete programming methods, because the components w_g variations are given on a discrete set $\overline{1, W_g}$.

Technological systems used in the manufacture of parts of devices and their assembly are discrete systems, so to model and optimize their work should use appropriate methods [11].

3. Method choice for modeling of production systems

The production system in General is a system with a fixed number of equipment (system units) that process a fixed number of parts (perform certain work).

Unfortunately, today there is no single method of modeling production systems in general, ie those that would adequately and with sufficient accuracy would describe the parameters of production systems of different structures, so to model a particular type of system, or at least several closely related types of various mathematical models. They are somehow able to model the production system, but usually each of them has its limits of application.

Models obtained by linear integer programming can only be used if a large number of constraints are imposed on the problem. In addition, to apply these methods, it is necessary to obtain the appropriate dependencies, which could be used to calculate the parameters of the system. Therefore, mathematical programming methods can be used as optimization methods in the presence of well-formalized system models [11].

Models of queuing systems are acceptable only for workflows with a random number and time of passage, because they use the apparatus of probability theory. You can usually consider degenerate cases where a random stream is replaced by a stream with predefined parameters. Therefore, we will consider deterministic queuing models that describe very well processes similar to those that need to be modeled. But such models are very different from each other depending on the type of system structure.

Models based on the provisions of graph theory differ from others by the simplicity and clarity of representation of both input and output data, and the image of the structure of the system itself.

Methods of classical modeling and optimization are well studied, widely used in theoretical problems, but have several significant shortcomings, in particular in terms of modeling systems in their application it is difficult to develop an adequate objective function that would satisfy the limitations of this method. would be able to interpret the results of further calculations, in particular the results of model optimization.

Statistical methods have been used for a long time and allow to determine the factors that most affect the characteristics of the system. However, they require a large amount of experimental data and therefore are more likely to be useful for solving problems of optimization of empirical processes, ie where it is impossible to establish unambiguous relationships between system parameters.

Structural-logical method of modeling is acceptable from the point of view of clarity of representation of system and calculations of its parameters, quite well algorithmized, has good convergence at

application of the corresponding optimization methods, and also is suitable for modeling of systems with various types of structures. clarity of presentation of the system.

Based on the analysis of methods of modeling production systems in order to optimize their work, it is established that the most interesting are the structural-logical method of research of technological systems and methods based on graphical representation of production structures using Petri nets. These methods are discussed in this article.

4. Structural and logical method of modeling and optimization of production systems

There are two main directions in the methods of research of production systems: general (abstract) systems theory, which studies the behavior of the system out of connection with its structure, as the ratio of inputs and outputs, and structural systems theory, which studies the functioning of the system depending on its structure.

The possibility of constructing a deterministic theory of service systems on the basis of the mathematical apparatus of infinite logic and logical determinants was first shown in, where the problem of synthesis of one class of static systems was solved. Subsequently, the possibility of applying this apparatus to the synthesis of other classes of systems, as well as to their analysis was shown.

The advantages of the apparatus of infinite logic and logical determinants are realized within the structural-logical approach to the study of service systems, which involves structural representation of the studied system and expression of its characteristics through the characteristics of subsystems using infinite logic and logical determinants.

Structural-logical method does not have most of the shortcomings of other methods of modeling and optimization of production systems, ie it is acceptable in terms of clarity of the system and calculations of its parameters, quite easy to formalize, has good convergence in the application of appropriate optimization methods, and that most importantly, suitable for modeling systems with different types of structures, namely: serial, parallel, parallel-serial and serial-parallel. This approach makes it possible on the basis of a small number of such algorithms to calculate, analyze and synthesize the optimal structure of the production system.

5. Construction of mathematical models of production systems

The tasks of studying systems are very diverse and are largely determined by the class of the studied system. However, there are universal types of problems that are essential for many classes of systems: representation, calculation, analysis and synthesis.

Representation of the system is a representation of all given information about the system in a compact form, which facilitates the description of the system, as well as the formulation and solution of problems of its calculation, analysis and synthesis.

The calculation of the system is to determine the numerical values or expressions of various characteristics of the system according to the given structure of the system, the mode of its operation (for the service system - also the order of work coming to it) and the numerical value of its blocks.

The problem of system calculation is important for all classes of systems. It reveals the possibilities of existing natural (biological, social) and underlies the design of artificial (technical, organizational and economic) systems.

The analysis of the system consists in determining the type of dependence of various characteristics of the system functioning on its structure, the mode of its functioning (for the service system - also the order of execution of works in it), the values of its blocks.

The analysis allows to establish the degree of influence of these three factors on the characteristics of the system. Due to this, it is possible to perform calculations of accuracy (stability) of the

system at different values of its parameters and structure and calculations in the design of systems in order to achieve the desired values of system characteristics by some change in their parameters and structure.

The synthesis of an arbitrary system consists in determining its structure and mode of operation for a given purpose of the system, the values of the parameters of its blocks and the required values of the characteristics of the system.

The synthesis of the service system is to find its structure and the order of execution of works from a given set of works to be performed, the values of the parameters of the blocks that form the structure of this system, and the required values of various characteristics of the system.

The task of system representation is important only for complex systems, while the tasks of calculation, analysis and synthesis are essential for any system - both simple and complex. In our case, service systems are considered, for which the problems of representation, calculation, analysis, and synthesis problems are solved in the form of the problem of finding the optimal order of execution of a given set of works in the system, which provides optimal values of certain system characteristics. The structure of the system and the parameters of its blocks are considered specified.

The paper considers deterministic problems of representation, calculation, analysis and synthesis of service systems with a typical structure (serial, parallel, parallel-serial, serial-parallel), with different modes of operation of units and submission of works, with the possibility of imposing restrictions on the operation of units.

Here are the mathematical models for each type of system, according to the problems to be solved. The tasks of calculation and analysis of the service system are respectively:

- a) calculation of its various characteristics (performance, load, etc.) in accordance with the specified similar characteristics of its units, the scheme of their connection, the number of works entering the system, and the mode of operation of the system;
- b) determining the nature and degree of influence of all given factors on the characteristics of the system.

The solution of the first problem must precede the solution of the second.

The complexity of solving both problems significantly depends on the scheme of connection of blocks to the system (serial, parallel, etc.), the mode of operation of the system (single-program or multi-program, waiting for work or without waiting, etc.), the number of jobs entering the system. A single-work system can only be without waiting and with a single-program execution mode.

Analysis of such systems is not a problem and is not considered here. Of the other systems, serial systems are the most convenient for calculation and analysis. Consider a system in the form of m series-connected blocks, designed to sequentially perform m different operations.

The system receives n different works, each of which breaks down into m of the above operations. Opening times a_{ij} ($i = \overline{1, m}$) for jobs j ($j = \overline{1, n}$) given by the matrix: $A = \|a_{ij}\|$.

Execution of works in the system can be carried out in two modes: single-program and multi-program.

In the first mode, first all the operations of the first work are performed sequentially, then in the same order all the operations of the second work, and so on.

In the second mode of operation are started in the system and pass its successive blocks $1, 2, \dots, m$ in the same order $P_n = (j_1, j_2, \dots, j_n)$; here j_k is the number of the work that follows the k -th in order.

Thus moments of receipt of works in system are not specified (free on time of receipt of works), the block 1 is loaded and starts to carry out the operation in the next work j_k immediately after release from the previous work j_{k-1} (ie in the block there are no downtimes); loading of the first work j_1 occurs at the initial moment $t = 0$.

However, block 2 begins to perform its second operation in the next job j_k not immediately after the release of the previous job, but only after the end in block 1 of the first operation of work j_k .

Similar time relations between the operation of units 2 and 3, 3 and 4, ..., $m-1$, m . Thus, in blocks 2, 3, ..., m downtime is possible. But it is possible that the work that comes to the unit, finds him busy with previous work.

In this case, the unit works without downtime, but the work coming to it is waiting, forming a queue served by the unit as a rule: first come - first served. So, a multi-program system is a standby system.

For a *serial system*, the total time $To(m, n)$ of the passage of all n works through all m blocks of the system with a single-program mode of execution of works is equal to the summing logic determinant from the matrix $A = \|a_{ij}\|$ times of operations, and for the case of multiprogram mode $Tm(m, n)$ – disjunctive logic determinant from the matrix $A = \|a_{ij}\|$.

In the case of a **parallel system**, it is represented in the form of m parallel connected blocks 1, 2, ..., m , which are designed for parallel performance of the same type of work. The blocks are functionally equivalent, ie they can perform each of the works.

However, the speed of the blocks in the general case is different - the execution time in the work block is a_{ij} . Times a_{ij} form a matrix of working times $A = \|a_{ij}\|$ sized $m \times n$.

The system works in multi-program dynamic mode as follows. Works 1, 2, ..., n are fed into the system in a given order $Pn = (j_1, j_2, \dots, j_n)$, where $j_k \in \{1, \dots, n\}$, but without specifying the moments of receipt, ie free time.

In this case, at the initial moment $t = 0$ at the same time work j_1 is loaded into block 1 (which immediately begins to perform its operation), similarly work j_2 – in block 2 and so on – work j_m – in block m .

After that, all blocks of the system are loaded by performing the first m works $j_1, \dots, j_m$. Therefore, the next job j_{m+1} will have to wait until the first $j^{(1)}$ of the loaded jobs $j_1, \dots, j_m$ is performed, and then take its place in the vacated block.

The next job j_{m+2} will have to wait for its loading into the system until the moment when the first of the new set of jobs $\{j_1, \dots, j_m, j_{m+1}\}$ that are currently in the system and so on will be performed. It follows that the considered system works without downtime (ie with a load equal to 1) in the standby mode of the start of its execution.

Simultaneously with the tasks of calculation and analysis, the problem of system representation is solved, using the apparatus of ordinal logical determinants.

Matrix $T(m, n) = \bigvee_{k=1}^n t_k$ is the basic ratio for calculating the system speed. It reduces the definition of the performance characteristic of the system $T(m, n)$ to the calculation of the vector of moments of completion of work in the system.

In the case of using **parallel-serial and serial-parallel systems**, they are represented in the form of M series-connected stages (groups, blocks), designed to perform work consisting of M different operations.

Let the i degree ($i = \overline{1, M}$) serves to perform the i -th operation and is a subsystem in the form of m_i parallel connected blocks 1, 2, ..., m_i . All blocks of one stage are functionally equivalent, ie configured to perform one operation, and the i -th stage can perform simultaneously m_i such operations of the same type (according to the number of blocks in it).

We believe that all blocks of one degree have the same speed (ie degrees are homogeneous in blocks). The system receives a set of n different works, each of which consists of M of the above operations. Time a_{ij} execution of the i -th operation ($i = \overline{1, M}$) for job j ($j = \overline{1, n}$) are given and form a matrix $A = \|a_{ij}\|$.

Execution of jobs in the system is possible in two modes: single-program and multi-program.

In the first mode, first all operations of work 1 are performed sequentially, then in the same order all operations of work 2 and so on.

In the second mode, the system operates as follows. The order $P_{1n} = (j_{11}, j_{12}, \dots, j_{1n})$ of start of works on the first operation (the first stage of system) where j_{1k} – number of the work started k -th on an

order is specified. At the same time the moments of receipt of separate works are set, that is we have system with free on time receipt of works.

Execution of the first operation in the next work j_{1k} begins as soon as among the blocks of the first stage engaged in execution of this operation in the previous works $j_{11}, \dots, j_{1,k-1}$ any block is released.

Execution of any i -th ($i = \overline{1, M}$) the operation in the next work j_{1k} begins as soon as the execution of the previous ($i-1$)-th operation in this work ends and among the blocks of the i -th degree, occupied with the execution of the i -th operation in the incoming j_k works, any block will be released.

The mathematical apparatus of infinite logic can serve as an adequate means of describing deterministic service systems. This adequacy is manifested in the fact that for an arbitrary system, any characteristic of functioning can usually be expressed through the parameters of the system using logical operations of infinite-valued logic (sometimes supplemented by ordinary algebraic addition).

In this case, formally, the difference between the characteristics comes down to the fact that some of them receive simple expressions (containing few of these operations), and others - complex (because they contain many operations). Using the rules of equivalent logical transformations developed in infinite logic, the received expression of the characteristic of functioning can always be led to this or that convenient kind. This type depends on the system problem to be solved.

Thus, to solve the calculation problem, the most convenient is the minimum expression of the characteristic that contains the smallest possible number of logical and other operations; to solve the problem of analysis - the expression of a characteristic with a selected parameter, the impact of which on the system is analyzed; to solve the problem of synthesis - the expression of characteristics in a form that is sensitive to changes in the order of work in the system.

This possibility of flexible representation of different characteristics of systems functioning in terms of operations of infinite logic opens the fundamental possibility of the same, based on the rules of equivalent logical transformations of infinite logic, solving the whole set of problems of systems research - calculation, analysis, synthesis.

This possibility of the same solution of problems of calculation, analysis and synthesis of service systems using the apparatus of infinite logic is directly realized only for fairly simple systems, where the number of blocks is small, and the links between them are not developed. In complex systems due to the presence of a large number of blocks with developed links between them on the way to the implementation of this possibility there are additional difficulties associated with the need to solve the problem of system representation.

In overcoming these difficulties the main role is played by the mathematical apparatus of logical determinants. Since the logical determinant is a parameter of the enlarged description of the studied system, they allow to present all given information about the system in a compact, accessible form, which makes the system "simple" and opens the way to its study by the above methods of studying simple systems based on the apparatus of infinite logic. In addition, the apparatus of logical determinants allows to make in the process of studying complex service systems and a number of other significant simplifications.

The method of modeling and optimization of loading of production technological systems on the basis of structural-logical approach to the study of complex systems is tested on real examples.

The use of structural-logical approach to modeling and optimization of production systems has the following advantages:

a) unification with the help of logical determinants of computational procedures in the study of systems leads to the fact that all tasks of calculation and analysis, as well as the synthesis of complex systems are reduced to the calculation of certain logical determinants, ie are the same from a computational and mathematical point of view;

b) obtaining analytical conditions for the optimality of the order of work in the system and on their basis - the procedures for the synthesis of some classes of complex systems have a reduced complexity of calculations;

c) modification of the procedure of branches and boundaries, which is used in the synthesis of complex systems to improve its accuracy and speed, allows to intensify the clipping of unpromising options by additional use of information contained in optimal conditions, and obtaining a more accurate estimates that in addition, it has reduced computational complexity.

The above advantages of using infinite logic and logical determinant are realized within the structural-logical approach to the study of production systems, which involves structural representation of the studied system and expression of its characteristics through the characteristics of subsystems using infinite logical logic and logical determinant.

6. Conclusions

The article theoretically substantiates and implements mathematical methods of modeling production systems, which allow to choose rational conditions for their work.

It is shown that increasing the efficiency of instrument-making production can be achieved by modeling and optimizing the equipment load of production systems.

The analysis of modeling methods for production systems has shown that at the decision of this problem it is expedient to apply modern methods of mathematical and simulation modeling based on use of the structural-logical approach to mathematical modeling of systems.

Methods of infinite logic and logical determinants allow to describe the mathematical model of the production system and its characteristics, and the method of branches and boundaries - to optimize its work. The basic provisions of infinite logic and ordinal determinants, on which the structural-logical approach to the study of complex systems is based, which include production systems in instrument making, allow to create a mathematical model of the system of arbitrary structure.

The actual application of this method of modeling production systems can reduce non-production losses of time, thereby saving production resources without the use of any other measures of administrative or technical nature.

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Atmospheric Observation and Radio Signal Measurements over the Black Sea Region for Assessment of Tropospheric Radio Propagation and Potential Radio Interferences.

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Abstract: Due to various interferences arising from the tropospheric propagation of radio waves over big water basins, it is necessary to study in detail the mechanisms of propagation and to improve the existing models for determining propagation factor or path loss profiles at different frequencies, especially in UHF bands, caused by the growing interest of mobile communications and especially 5G technologies. To get enough information about radio wave propagation over the Black sea area, the state of atmosphere above points of interest is studied in detail and the results are compared with real measured radio signals distributed between those points. The results are compared with basic theoretical computed models. The results showed more than 10 dB and from 6 to 10 dB difference respectively for VHF and UHF between measurement and computed with Three way path loss model EMF levels for the favorable cases which might be due to additional ray in the receiver. A clear relationship between received EMF levels and wind speed but in combination with different abnormal tropospheric environments and relationship between absolute value of modified refractivity and the levels of received signals for the surveyed regions.

Keywords: MODIFIED REFRACTIVITY PROFILE; DUCT MEASUREMENTS; DUCT OCCURRENCE; RADIO WAVE PROPAGATION OVER SEA; RAY MODEL.

1. Introduction

The state of the atmosphere has a great impact over radio wave propagation. Temperature, moisture and pressure are the variables that influence refraction. The type and the amount of refraction produced by these variables can be determined by understanding the relationship of each property to refractivity (N). An increase with 1 °C in temperature caused decrease with nearly 1 N units of the amount of the refractivity. Usually, in a standard atmosphere temperature decrease with 6.5 °C per 1 km which does not have a great impact over refraction, but an exception to this occurs with temperature inversion. Moisture produces the greatest change of refraction. In the lower atmosphere the pressure has a small effect. Ununiform refractivity makes the radio wave bend. The change of refractivity with altitude is referred to as the N -gradient, which determines its type and intensity. The larger positive or negative N -gradient, the more radio waves bend. There are four main propagation types for different refractivity conditions, respectively different N -Units (see Fig. 1).

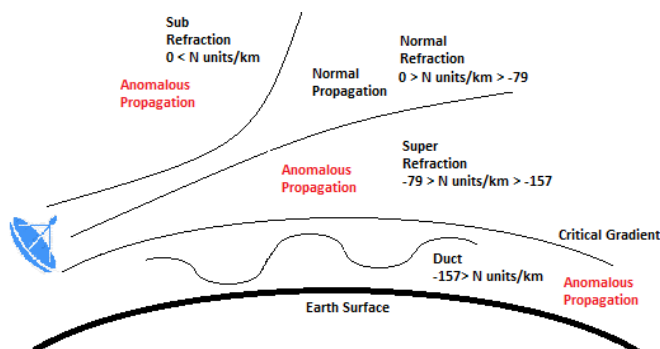


Fig. 1 Types of refraction and atmospheric propagation.

Since refractivity N does not take into account the curvature of the earth, it is more convenient to use Modified refractivity (M) instead. The formula for M is given by:

$$(1) \quad M = (n - 1)10^6 + 0.157h,$$

where n is index of refractivity and h altitude. Another way to evaluate M by using measurable variables is [1]:

$$(2) \quad M = \frac{77.6}{T} \left(P + \frac{4810e}{T} \right) + 0.157h,$$

where P is total atmospheric pressure (mb), T is atmospheric temperature (K) and e is water vapor pressure (mb). The most interesting propagation mechanisms from the researchers point are the tropospheric ducts. Ducts can greatly extend the ranges of radio waves. There are four basic types of ducts: surface, surface-based, elevated and evaporation ducts. Due to various interferences arising from the tropospheric propagation of radio waves over big water basins, it is necessary to study in detail the mechanisms of propagation and to improve the existing models for determining propagation factor or path loss profiles at different frequencies, especially in UHF bands, caused by the growing interest of mobile communications and especially 5G technologies. To get enough information about radio wave propagation over the Black sea area, the state of atmosphere (which includes the parameters needed for determination of the refractivity profiles) above two points of interest Varna, Bulgaria and Sevastopol, Crimea peninsula and state of the water are studied in detail. To represent modified refractivity profile, a model for visualization is used. On the other hand a measurement of VHF and UHF signals, propagated between those two cities is performed. The results are compared with basic theoretical model for determining path loss and its two and three way extended sub models.

2. Modeling Modified Refractivity profile

Two years period (from 2019 to 2020) meteorological data are used to determine the occurrence of all type of ducts above two points over Black sea. For the region of Varna, are used meteorological data from 13 measuring points at different altitude from 2 to 311 meters above sea level (ASL). For the region of Sevastopol are used 6 measuring points at different altitude from 2 to 345 meters ASL. Meteorological data from all 19 measuring points are reported at the same time and period. By using methods describe in [2], the modified refractivity profiles for the points of interest are evaluated, reconstructed and graphically represented for the periods with measured highest field strength levels for five different frequencies, (see Figure 2, Figure 3, Figure 5 and Figure 6). That periods with measured highest electromagnetic field strength (EMF) level are selected from measurement complain, produced again for the same two years period. For the 2019 year the highest EMF levels were measured on 09 August [3] and for the 2020 year on 02 September. The measured EMF levels are compared with the measured wind speed over the two cities for the same period. The results are compared and graphically represented (see Figure 4 and Figure 7).

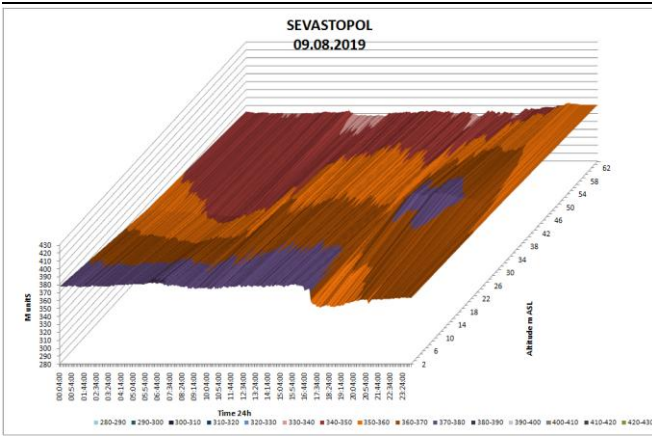


Fig. 2 M units for the region of SEVASTOPOL, period 09.08.2019

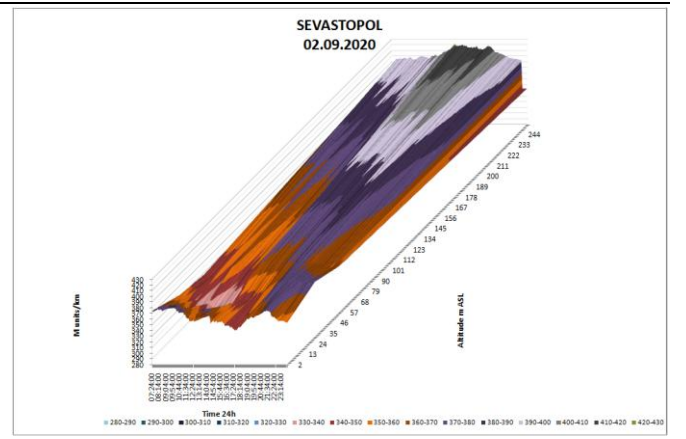


Fig. 5 M units for the region of SEVASTOPOL, period 02.09.2020

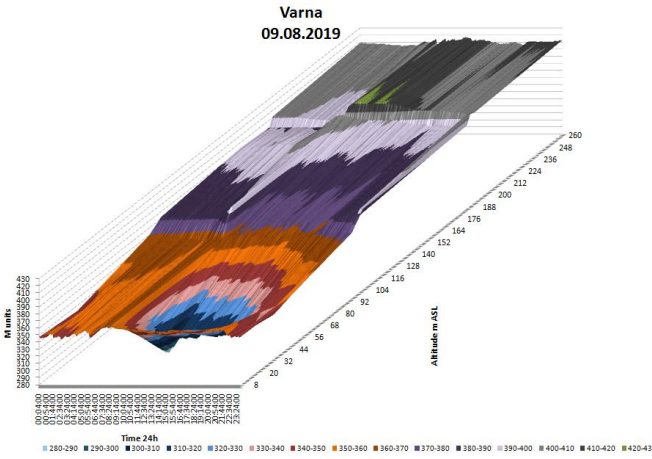


Fig. 3 M units for the region of VARNA, period 09.08.2019

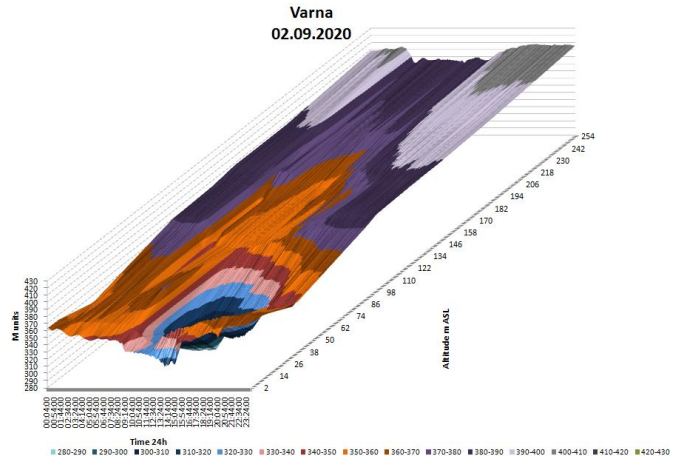


Fig. 6 M units for the region of VARNA, period 02.09.2020

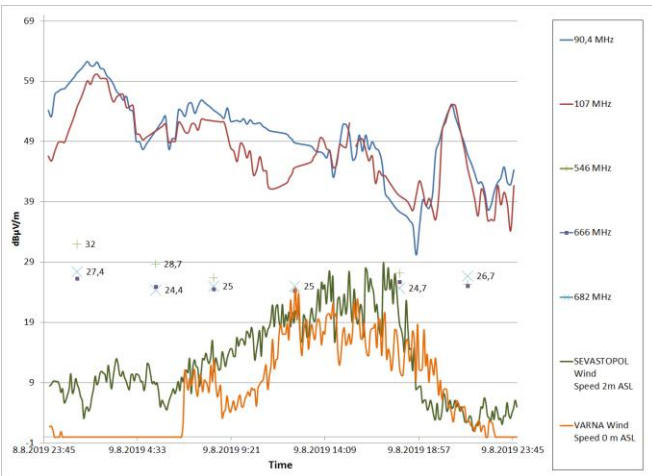


Fig. 4 EMF levels in dBμV/m for 90.4 MHz 107 MHz, 546 MHz, 666 MHz and 682 MHz. Wind speed in km/h for the VARNA (orange) and SEVASTOPOL (green). Date of measurement: 09.08.2019

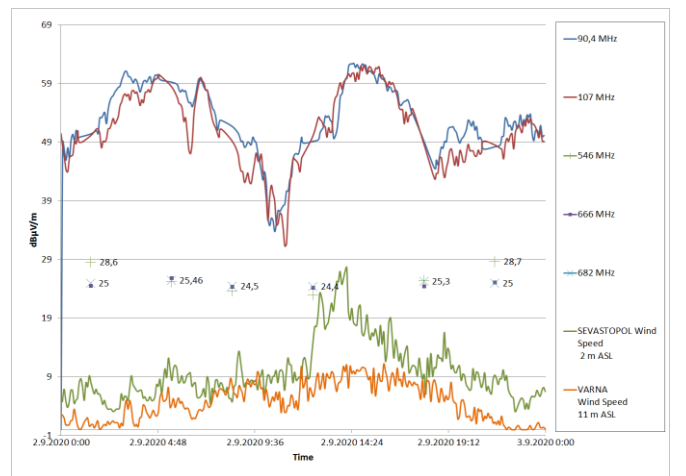


Fig. 7 EMF levels in dBμV/m for 90.4 MHz 107 MHz, 546 MHz, 666 MHz and 682 MHz. Wind speed in km/h for the VARNA (orange) and SEVASTOPOL (green). Date of measurement: 09.08.2019

The refractive profiles for the most favorable periods measured on 09.08.2019 and 02.09.2020 over Varna looks very similar which determined the similar results from the measurement campaign.

3. Basic Channel Models for Radio Wave Propagation

For the radio wave propagation in free space, the propagation loss can be predicted by the FSL model:

$$(3) \quad L_{FSL} = 20 \log \left(\frac{4\pi d}{\lambda} \right),$$

where L_{FSL} is the free space loss in dB, λ is the wave length, and d is the propagation distance in meters.

The needs to fit the local oscillations resulted from the destructive summation of sparse multipath signals the ray trajectory-based path loss models can be used. This model can geometrically identify the trajectories of the most dominant rays arrived at the receiver, thus the phase shift of each ray is characterized and considered in the path loss calculation, therefore providing a better description of the local peaks and nulls of the received signal strength. When a reflected ray from the sea surface exists besides the LoS path (direct ray), the propagation loss could be predicted by a 2-ray path loss model, which can be simplified as [4]:

$$(4) L_{(h_t, h_r)} = -10 \log_{10} \left(\left(\frac{\lambda}{4\pi d} \right)^2 \left(2 \sin \left(\frac{2\pi h_t h_r}{\lambda d} \right) \right)^2 \right),$$

where L is the 2-ray propagation loss in dB, and h_t , h_r are the heights of a transmitter and a receiver in meters. If a homogeneous evaporation duct layer exists pathloss can be expressed as a simplified three-dimensional model [4]:

$$(5) L_{(h_t, h_r, h_e)} = -10 \log_{10} \left(\left(\frac{\lambda}{4\pi d} \right)^2 (2(1 + \Delta))^2 \right),$$

where:

$$(6) \Delta = 2 \sin \left(\frac{2\pi h_t h_r}{\lambda d} \right) \sin \left(\frac{2\pi (h_e - h_t)(h_e - h_r)}{\lambda d} \right),$$

and h_e is evaporation duct height.

4. Measurement and comparing results. Discussion

Brief transmitting and receiving point's data are represented in Table 1. For the interested reader's detailed information about these points, its situations and all other information could be found in [3].

Table 1: Transmitting and receiving points data

Transmit points Sevastopol				Receive point Varna		Distance m	Sea path
Frequency MHz	TxPr Kw ERP	Ant. height ASL m	Ant. Pol.	Ant. height ASL m	Ant. Pol.		
90.4	3	280	V	161	V (lp)	484	467
107	3	178	V		V (lp)	479	466
546	1	287	H		H(n)	484	467
666	1	287	H		H(n)	484	467
682	1	287	H		H(n)	484	467

The results from measurement survey are compared with basic theoretical model for determining path loss (3) and its two (4) and tree way (5) extended sub models (Table 2), associated with abnormal tropospheric radio wave propagation, under reflected or/and duct conditions. As a duct height is taken 40 meters (see Figure 10).

Table 2: Comparing propagation models with measured data

Frequency MHz	Free space model	Two way model	Tree way model	Measured dBμV/m 09.08.2019		Measured dBμV/m 02.09.2020	
				Min EMF	Max EMF	Min EMF	Max EMF
90.4	46,2	37,2	52,6	30,2	62,3	33,8	62,5
107	44,9	37,5	51,4	34,2	62,2	31,3	62,1
546	24,4	30,2	38,3	24,1	32	23	28,7
666	24,2	30,0	38,2	24,3	26,3	24,2	25,2
682	26,1	31,1	38,8	24,6	27,4	24,4	25,1

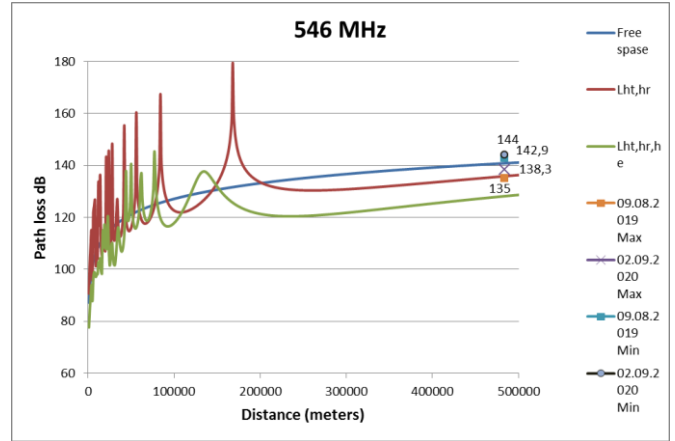


Fig. 8 Free Space, Two way and tree way path loss models compared with maximum value of real 564 MHz propagated signals

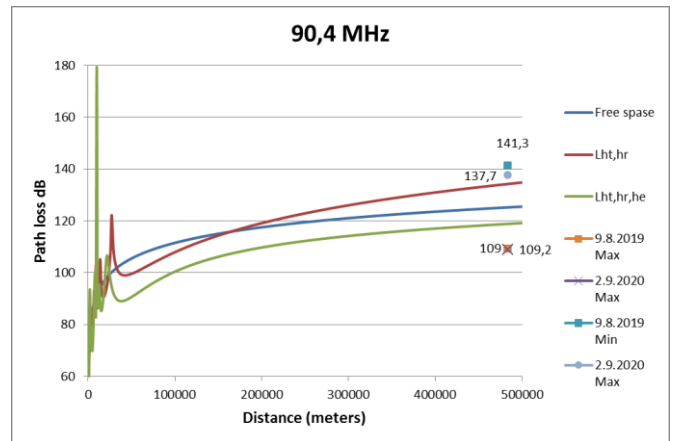


Fig. 9 Free Space, Two way and Tree way path loss models compared with real VHF propagated signals

The obtained results for propagation loss (Path loss) for above mentioned frequency could be treated as a maximum achievable for this specific path profile.

When comparing the results it could be seen that Two way path loss model gives a good results for highest EMF levels at 546 MHz (UHF) but here is good to be mentioned the presence of well define duct over Varna. When comparing the results with Tree way model inaccuracy is between 6 to 10 dB. Free space model produced a good result for the worst case.

None of those models give a good results for the 90,4 MHz (VHF). Inaccuracy is more than 10 dB with the most favorable model. Thus, when abnormal most favorable tropospheric conditions occur over this region VHF signals propagate in the troposphere by at least another 1 additional ray. Two ray model gives relatively a good results for the worst case.

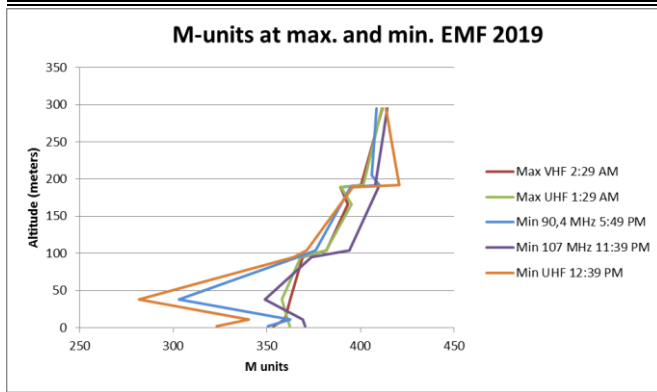


Fig. 10 M units profile for the region of VARNA at maximum and minimum EMF levels, period 09.08.2019

The difference between time of minimum for 90,4 MHz and 107 MHz are due to refractive profile at transmitting point because of different antenna heights (note that the frequency and the path are almost the same).

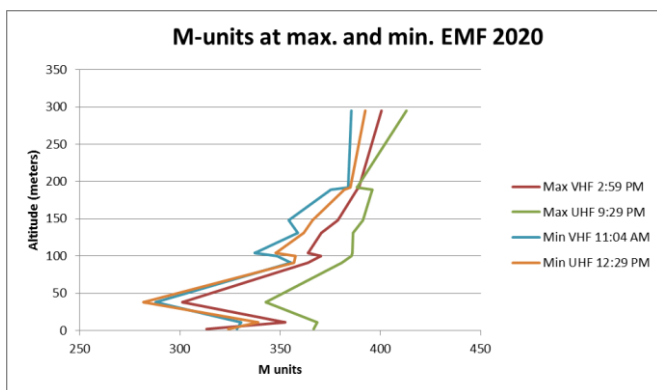


Fig. 11 M units profile for the region of VARNA at maximum and minimum EMF levels, period 02.09.2020

The overall decreasing at M units caused decreasing in EMF levels and vice versa.

Table 3: Wind speed at 4 different altitudes over two cities where respectively transmitters and receiver are located for the most favorable and unfavorable period in 2019.

WIND SPEED 2019 km/h						
	MAX EMF levels			MIN EMF levels		
Location /meters ASL/	UHF	90.4	107	UHF	90,4	107
SEVASTOPOL						
2	8,7	5	8,7	20,9	7,9	3,1
31	7,7	4	4,4	-	12	0
VARNA						
0	0	0	0	24,7	9,3	0
38	0	0	0	10,8	8,4	0

Figure 4, Figure 7, Table 3 and Table 4 showed the clear relationship between relieved EMF levels and wind speed. But this relationship must be looked at a different way from the influence of refractivity, because the effects of refractivity can be measured by its absolute values. But the wind effects are specific at any different region and are not determined by its absolute values. They depends on that, if the propagated rays or how many of them contacts with the water surface. For example: if the radio waves (or how many of them) propagate by surface or surface-based duct the influence is grater that if they propagate by the elevated duct or super refraction.

Table 4: Wind speed at 5 different altitudes over two cities where respectively are located transmitters and receiver for the most favorable and unfavorable period in 2020.

WIND SPEED 2020 km/h						
	MAX EMF levels			MIN EMF levels		
Location /meters ASL/	UHF	90.4	107	UHF	90,4	107
SEVASTOPOL						
2	15,1	18,3	16	9,3	10,2	6,7
57	8,9	9,7	9,3	0	2,5	3,7
VARNA						
0	0,9	7,9	3,3	2,8	3,7	6,4
11	5,6	10	10,6	1,3	2,9	3
38	9,6	21,2	23,6	0	5,4	1,9

5. Conclusion

Measurement survey and exploration of the state of the atmosphere and propagation of radio signals on five different frequencies in VHF and lower UHF bands are produced over part of North West Black sea area. The results are compared with basic theoretical computed models and its two and tree way extended sub models associated with abnormal tropospheric radio wave propagation. They have showed more than -10 dB difference between measurement and computed three way path loss model for VHF frequency and between +6 to +10 dB for UHF in the favorable cases which might be due to additional ray in the receiver. Two way path loss model gives a good results for favorable cases at UHF band and for worst cases in VHF band. The results also showed a clear relationship between relieved EMF levels and wind speed but not from wind absolute value but in combination with different abnormal propagation environments. A clear relationship between absolute value of modified refractivity and the levels of received signals for the surveyed regions is observed.

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Injury prevention during childbirth: The model of obstetrician

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Abstract: During childbirth, a technique called manual perineal protection (MPP) is often used to prevent injuries of relevant tissues. The obstetrician uses his (or her) hand to apply certain forces at the perineum in order to decrease its excessive loading during child delivery. Amount of applied forces as well as the correct posture of the obstetrician during the MPP technique are based so far on the experiences and approach of the obstetrician himself (or herself). In order to assess the role of obstetrician and in order to optimize the MPP technique, mathematical models may be of use. This work presents a combination of both experimental measurement and mathematical modeling. In the experimental part, a unique device is developed to measure forces applied by obstetrician during real child delivery. In the modeling part, the obstetrician is represented with an active musculoskeletal human body model in an AnyBody Modeling System software. Providing forces and muscle activities of the model may lead to the assessment and optimization of the MPP technique.

Keywords: VAGINAL DELIVERY, MANUAL PERINEAL PROTECTION, ANYBODY MODELING SYSTEM

1. Introduction

During a vaginal delivery, injuries of relevant tissues may occur such as ruptures of perineum, levator ani muscle and the obturator muscle [1]. In fact, only 9.6 % and 31.2 % of women deliver with an intact perineum at their first and second births respectively [2]. These injuries may have consequences in future in terms of female pelvic floor dysfunctions (perineal pain, anal incontinency, dyspareunia) [3].

In order to prevent injuries during childbirth, a technique called manual perineal protection (MPP) is often used [4]. The obstetrician uses his (or her) hand and fingers to apply certain forces at the perineum in order to decrease its excessive loading during child delivery. Amount of applied forces as well as the correct posture of the obstetrician during the MPP technique are based so far on the experiences and approach of the obstetrician himself (or herself). Still, proper execution of the MPP technique is a complex problem with lots of obstetrics variables [5].

In order to assess the role of obstetrician and in order to optimize the MPP technique, mathematical models may be of use. Here, we present a combination of both experimental measurement and mathematical modeling. At first, it is essential to determine forces applied by the obstetrician hand and fingers during the MPP technique. Although there are existing devices on the market (see e.g. [6]), these are not suitable for our application. Therefore, we develop our own experimental measurement system in a form of a glove for obstetrician. It records forces that are exerted by the obstetrician hand during a real delivery.

These data are used in the mathematical modeling of child delivery. The obstetrician is represented with a musculoskeletal model in the AnyBody Modeling System (AMS, Aalborg, Denmark, Version 7.2, AMMR 2.2.2) [7]. Here, human body is formed of rigid bones that are interconnected via joints based on real anatomy [8]. Muscles, tendons and ligaments are considered using models that enables active motion of the whole body model [9]. Kinematics of the AMS model is prescribed here using the data from the motion capture system during a delivery with physical model, see e.g. [10]. Finally, the results in terms of muscle activities of individual muscles are obtained.

2. Experimental measurement device

In the MPP technique used in this study, the obstetrician applies the force of his (or her) dominant hand at the perineum via thumb, index finger and the middle finger. The thumb and the middle finger press anterolaterally to the fourchette to reduce midline perineal strain. The flexed middle finger is used to apply pressure against the perineal body to facilitate the process of the fetal head extension. The non-dominant hand controls the speed of the fetal head expulsion and facilitates the fetal head extension [11].

To record these forces during this particular technique, we develop our own measurement glove. It must be 100% safe for child and the mother, it needs to measure forces acting at three defined points, it must be very simple to use and finally it must be durable for repeated use. The proposed prototype is depicted in Fig. 1.

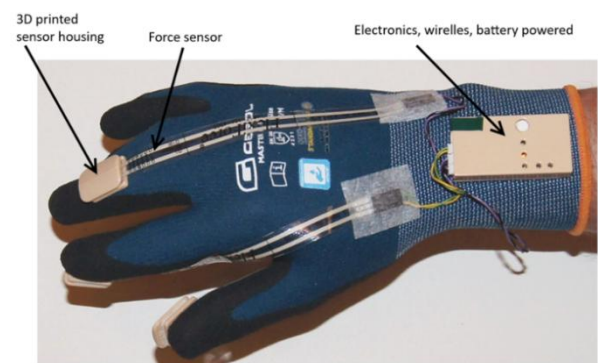


Fig. 1 Measurement glove with force sensors.

As force sensors, three force sensitive resistors Tekscan FlexiForce A201 are used. The device is powered with 3V coin battery and its rate is 100 samples per second. To achieve maximum safety, the glove is wireless and its electronics is isolated from obstetrician and touched surface. For each use, that is, for each child delivery, the glove is covered with new sterile surgical glove.

Experimental measurement includes real deliveries of 20 volunteers, see [11]. The forces are measured at the moment of the head expulsion. The example of measured data are depicted in Fig. 2. Here, evolution of forces in time for all the fingers are displayed for one particular volunteer.

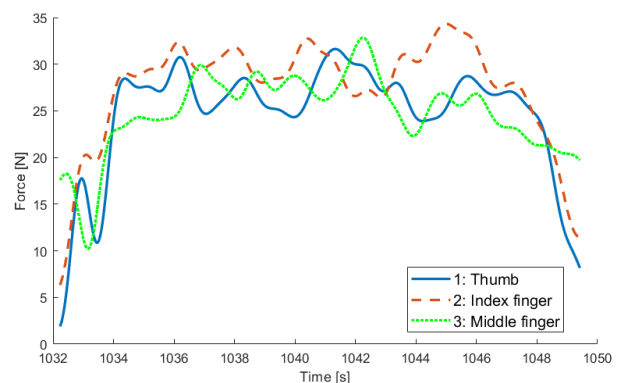


Fig. 2 Measured time-force dependencies of fingers during MPP. The curve no. 1 (blue) denotes thumb, no. 2 (dashed red) denotes index finger and no. 3 (green) the middle finger.

3. Obstetrician model

To represent the obstetrician, the AnyBody Modeling System is used. Here, human body is represented with rigid bones interconnected via joints. Active motion of the model is enabled by considering muscles, ligaments and tendons as type of simple models within AMS. Particular focus is given to the model of hand. In order to simulate the MPP technique properly, it is necessary to prepare the hand model in a great detail. Special attention is paid to the muscle attachment sites. Their proper definition allows us to determine exactly the positions and trajectories of individual muscles and hence to capture realistic moment arms and muscle activity during the MPP within the musculoskeletal model.

We use the MRI scans of real hand to obtain locations of muscle attachments. In AnyBody Modeling System individual muscles are replaced with user defined number of action lines or virtual muscle elements. These elements need to be placed within muscle volume in a way that respects anatomy of the muscle. Therefore, two tasks are to be solved in the mathematical modeling: placing required number of endpoints onto attachment surfaces and then pairing these endpoints in order to specify individual elements.

For the first task we use modified k-means algorithm. Given a finite set of points $\omega \subset \mathbb{R}^N$, $N \in \mathbb{N}$ and number $k \in \mathbb{N}$, original k-means method iteratively tries to approximate solution to k-partition problem. That is to partition set ω into k classes $\omega_1, \dots, \omega_k$ each corresponding with point $c_i \in \mathbb{R}^N$, $i = 1 \dots k$ called centroid, in such way that

$$\sum_{i=0}^k \sum_{x \in \omega_i} \|c_i - x\|^2$$

is minimal. In our setting, we use set of centres of gravity of the triangles in the mesh as a set ω . We modify the basic k-means method to ensure that the partition does not depend on density of points of the mesh [12].

The second task (pairing of the endpoints) is based on Euclidean matching problem in two dimensions. It can be proven that the minimality of total pairing distance ensures that no two line segments connecting paired points intersect. The minimal pairing is obtained by Hungarian algorithm which finds minimal matching in weighted bipartite graph [12]. The resulting minimal matching with pairs connected by lines can be seen in Fig. 3.

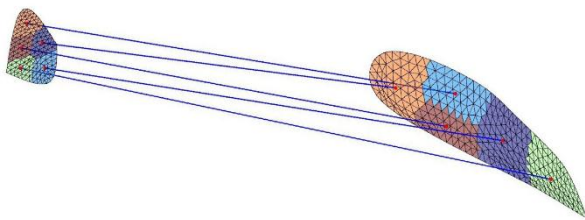


Fig. 3 Opponens pollicis connectivity with five muscle elements.

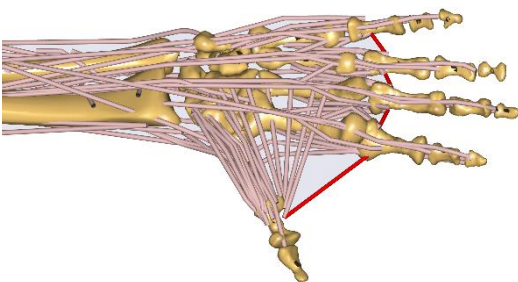


Fig. 4 Detailed hand model in AMS software.

The results from the k-means method are used to represent muscle attachment sites and muscle lines in the AMS model of the obstetrician hand. Individual muscles and tendons are represented with a type of simple muscle model [9] that includes contractile elements as well, see Fig. 4. Hence, both elasticity and muscle activity are included in the model. The geometry of the completed detailed hand model is depicted in Fig. 4. Finally, the hand model is embedded in the musculoskeletal model of whole human body within the AMS software to obtain the model representation of an obstetrician.

4. Simulation of the MPP and results

The AMS model of the obstetrician is employed for the simulation of the MPP technique. Here, the inverse dynamics method is used. It means that the motion of the obstetrician is prescribed and muscle activities and forces that correspond to that particular motion are calculated. To do that, an optimization algorithm is embedded in default in the AMS software. Typically, an objective function of a form

$$G = \sum_i \left(\frac{f_i}{N_i} \right)^p$$

is defined, where f_i is a force in an individual muscle, N_i is a normalization factor and p is a number ($p = 3$ by default). The objective function thus represents a higher order sum of muscle activities. Minimization of this objective function for prescribed motion leads to the solution in terms of resulting muscle forces and activities.

In this particular application, the kinematics data of the obstetrician performing the MPP technique are obtained using the motion capture system XSens that uses the IMU sensors instead of markers. Employing this device, the obstetrician performs the MPP protection technique during the child delivery with the physical model, see Fig. 5. While the right hand is used for the MPP technique itself, the left hand is used to support the head of the child model.



Fig. 5 Obstetrician performing MPP technique with physical model for kinematics data recording using XSens motion capture system.

Finally, all the experimental data gathered include forces exerted by hand of the obstetrician during a real delivery and the kinematics of the obstetrician during the MPP technique with the physical model. These are used as input data for the simulation of

MPP technique with musculoskeletal model of the obstetrician within the AMS software. The method of inverse dynamics is applied.

In fact, the MPP technique are simulated considering various postures of two obstetricians. The reason is to assess the MPP technique under varying conditions for its optimization. The example of the results is provided in Fig. 6. The musculoskeletal AMS model of the obstetrician performing the MPP technique in standing position is displayed. Colouring of individual muscles corresponds to the level of their activities calculated in the model. Namely, there is an increased muscle activity on the lower back due to the bent posture. This leads to increased joint reaction forces and hence it may cause increased problems within this body part.

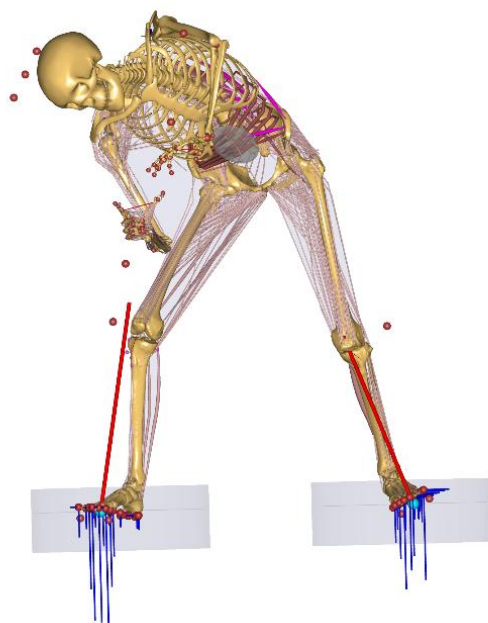


Fig. 6 Simulation of the MPP technique in the AMS software with the musculoskeletal model of the obstetrician. Coloured muscles correspond to their muscle activity.

5. Conclusion

The aim of this study is to present the abilities of mathematical modeling for improvements in medical field. Namely, the aim is to contribute to the knowledge regarding the manual perineal protection, i.e. the technique performed by obstetricians to prevent injuries of tissues during vaginal delivery.

The musculoskeletal model of hand is developed in great detail and embedded with the whole human body model in the AnyBody Modeling System software. To perform simulation of an obstetrician performing MPP technique, experimental data are necessary to gather as model input. Hence, unique measurement device is developed to record forces exerted by the hand of obstetrician during the delivery. Second, kinematics of the obstetrician is obtained during the delivery with physical model using the motion capture system.

The results of the mathematical modelling are obtained in terms of individual muscle activities and forces of the obstetrician. Hence, the MPP technique may be assessed and optimized from the perspective of the obstetrician and possible overloading of his or her body parts. In the example presented in this study, increased activity of the lower back muscles is obtained due to the bent postures. This indicates possible problems within this body part.

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Injury prevention during childbirth: A model of pelvic floor

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Abstract: During vaginal delivery women suffer with several kinds of injuries which may negatively influence their quality of life. Different techniques are used for perineal protection during the second stage of the delivery. A method called manual perineal protection (MPP) is used to decrease the risk of severe perineal trauma. In order to quantify this method a special measuring glove was designed and forces generated by the obstetricians during real deliveries were measured. Measured forces were then used in computer simulation of the MPP method. The forces were applied on a previously developed FEM model of the pelvic floor during simulation of the vaginal delivery. The stress distribution in the perineal area was monitored. Reactions of perineal tissues were evaluated. The simulations of childbirth with and without MPP were compared

Keywords: VAGINAL DELIVERY, FINITE ELEMENT MODEL, PELVIC FLOOR, MANUAL PERINEAL PROTECTION

1. Introduction

Female pelvic floor dysfunctions are very often associated with injuries of pelvic floor structures during vaginal delivery. It is reported that only 9.6% and 31.2% of women deliver with an intact perineum at their first and second births respectively [Smith]. Therefore, it is imperative that strategies that decrease the extent of perineal trauma are developed, assessed and promoted.

In the certain cases the method called manual perineal protection (MPP) can be used to successfully protect the integrity of the perineum during vaginal delivery [7]. Proper execution of the MPP is a complex problem with a high variation of obstetrical variables described by the accoucheurs [5]. Due to the nature of vaginal delivery, it is not possible to precisely repeat a modification of MPP in order to study its efficacy. Virtual modeling linked with measuring techniques seems to be a promising way how to improve the maneuvers and helps in better understanding of this topic.

The correct virtual modeling should always stay on relevant experimental data. (Several studies were published.) As the pilot research the stereophotogrammetry was presented [11]. Large deformations of the perineal skin were quantified, however, no information concerning acting forces was known. For this reason, a special measuring glove was designed and used by obstetricians during real deliveries. This unique measurement was published [10].

So far, the MPP has been simulated based on stereophotogrammetry data only [3,4]. The simplified model covering the rigid fetal skull and superficial perineal structures represented by a homogenous material were modelled. The forces applied by obstetricians were supplied by boundary conditions.

The main objective of this study is to improve the existing female pelvic floor FE model [6] and to simulate a delivery of a fetal head. The second aim is to simulate the MPP at the time of the head expulsion using hand forces measured during the real delivery.

2. FE Pelvic Model

Previously published finite element female model was used as a basis [6, 2]. Originally, the model consisted of the female pelvis, the levator ani muscle (LAM) with the fetal head modelled as a rigid body. Other surrounding structures were substituted by boundary conditions. For the refined FE model muscles forming the pelvic floor such as ischiocavernosus, bulbospongiosus and transversus perinei including anal sphincters and the anococcygeal ligament and the perineal membrane were added. The geometry of all structures was based on a live-subject's MRI data and anatomical cadaveric measurements. Complete model geometry is shown in the Fig. 1.

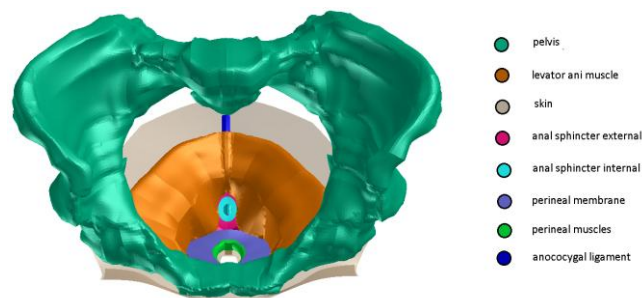


Fig. 1 Setup of the pelvic model.

The fetal head model and its trajectory through the pelvic floor structures was reconstructed based on the dynamic magnetic resonance of a vaginal delivery [1]. However, the fetal head was scaled up to ensure that its main dimensions corresponded to those of an average size term fetus.

Bones were modelled as rigid bodies, soft tissues as hyperelastic Ogden material to allow for large deformation. The muscle material constants were fitted using the stress-strain characteristic measured during a uniaxial tensile test and utilizing information from porcine samples or characteristics published previously in [2]. The perineal membrane was modeled as a layered membrane with perpendicular layers of fibers and a surrounding matrix. The skin was modelled by elastic shells. Material characteristics such as skin and ligaments were based on literature search.

3. Delivery Simulation

Using the new FE model, the vaginal delivery was simulated for the optimal fetal head size, position and orientation – i.e. left occipito-anterior position.

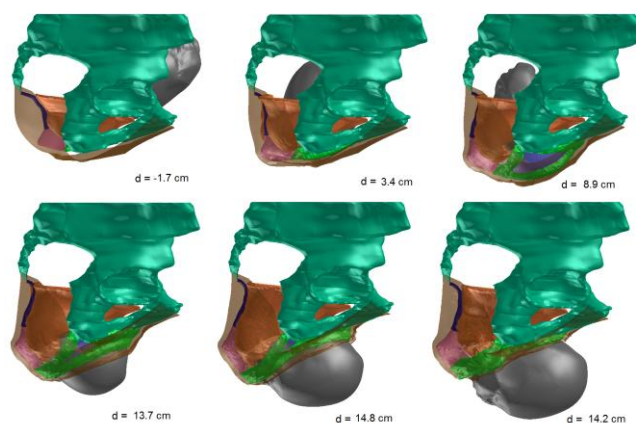


Fig. 2 Phases of the delivery in side view displayed in chosen stations marked as d.

The simulation was prepared and results were analysed by VPS. The stress and strain distribution of the pelvic floor structures during birth was analysed by the Virtual Performance Solution (VPS 9.0; ESI Group, Paris, France) commercial software. The head station was defined as the distance between the interspinous diameter and the head vertex. The interspinous diameter is the distance between the tips of the ischial spines. The vertex denotes the top of the head in the upright position. The delivery simulation starts with the head placed in the upper part of the pelvis then rotates and descends according to prescribed trajectories. The head in chosen positions – stations - is shown in Fig. 2.

4. Measuring of forces during MPP

Several variations of the MPP maneuver exists. The used Finnish technique of MPP (FMPP) involves application of the thumb, the index finger and the middle finger of the dominant hand on the perineal skin. The thumb and the middle finger press anterolaterally to the fourchette to reduce midline perineal strain. The flexed middle finger is used to apply pressure against the perineal body to facilitate the process of the fetal head extension. The non-dominant hand controls the speed of the fetal head expulsion and facilitates the fetal head extension [10].

Since it is difficult to evaluate the actual contribution of the individual components of FMPP in a clinical setting a special measuring glove was designed, see Fig. 3. Using this glove forces applied by the obstetrician during FMPP were measured. This right-handed glove was designed in order to gather forces generated by the obstetrician during the head expulsion. The wireless sensors are placed on the thumb, the index finger and the middle finger. The glove is a part of system, which collects, transfers and stores data onto a PC. All detailed information including pilot measurements are published in [10].

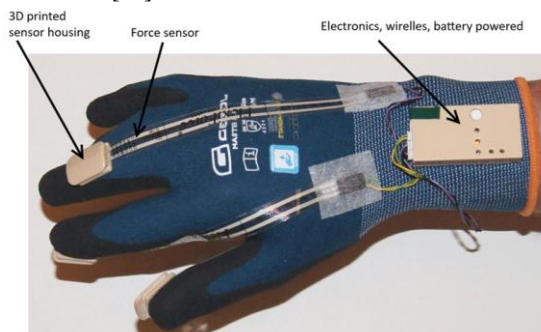


Fig. 3 Measuring glove with force sensor.

During the delivery the glove was put on the accoucheur's right hand and covered by the sterile medical glove. At the moment of the head expulsion the forces were measured

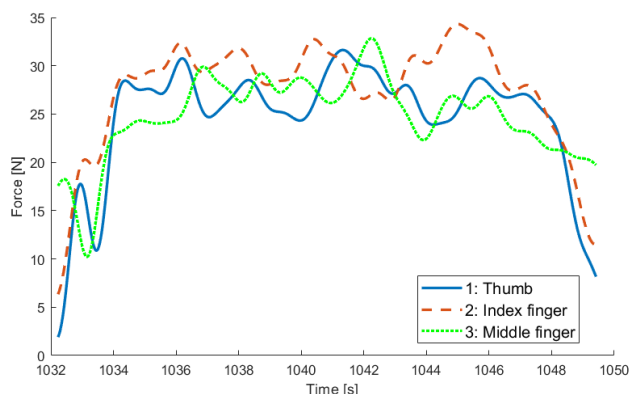


Fig. 4 Measured time-force dependencies of fingers during MPP. The curve no. 1 denotes thumb, no. 2 denotes index finger and no. 3 the middle finger.

. In [10] twenty first term spontaneous deliveries were undertaken by two expert obstetricians using the measuring glove. Measured samples were processed. The courses of finger forces of one chosen case are displayed in Fig. 4.

5. Simulation of MPP

The proper time-force dependencies of fingers of the one chosen delivery are implemented to the pilot simulation of the FMPP. As the first step the preliminary simulation of the “hands on” technique was prepared and only the pressure loading of fingers without head delivery were implemented to control perineal structures reaction. Further the complete delivery with “hands on” was simulated. The obstetrician fingers acting during the maneuver are supplied by prescribed pressure loading as is shown in Fig. 5. Measured forces are converted to pressures since the sensor surfaces are known.

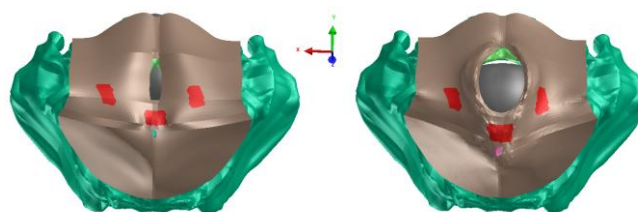


Fig. 5 Pelvis in inferior view at the beginning of the simulation (left) and with the head station at 11.4 cm (right). The positions of the finger sensors are red colored.

According to [3] the fingers during delivery are applied when the vaginal introitus is dilated to 8 cm anteroposteriorly and 4 cm transversely which corresponds to the head station equal to 11.4 cm in the presented model. At this moment, which corresponds to the beginning of the head expulsion, pressure loadings increase and continues till the end of the simulation.

6. Results and discussion

Our study confirmed the hypothesis that pelvic floor structures undergo large stress and deformation during the second stage of the labor, see Fig. 2. The caudal displacement of the LAM was 2.4 cm and 4.1 cm for the head station equal to 8.9 cm and 14.2 cm respectively. It corresponds to a 166% elongation of the LAM in the caudal direction. The perineal caudal displacement was 4.9 cm for the head station equal to 14.7 cm.

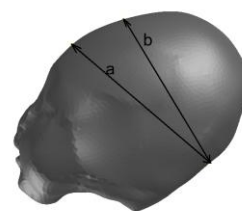


Fig. 6 Fetal head diameters; a) suboccipito-frontal, b) suboccipito-bregmatic diameter.

The stress values at the LAM were the highest at the anterior attachments to the tendinous arches when the head station was equal to 8.9 cm and reached 30.8 MPa. This was followed by a decrease in the LAM stress level as the stress in the perineal structures starts to increase with further head descent. The stress in the perineal body reached its maximum when the suboccipito-frontal diameter of the head was passing through the introitus. It was later than the priori expectation that this would happen when this area is stretched by the suboccipito-bregmatic diameter of the head. The suboccipito-bregmatic diameter passed through the introitus at the head station

equal to 14.7cm. Described head diameters are demonstrated in the Fig. 6. All monitored first principal stress values are summarized in the **Грешка! Источникът на препратката не е намерен.** and displayed in the Fig. 7.

Table 1 Summary of maximal values of the first principal stress on the LAM and the perineum muscles.

Muscle / region	Head station [cm]	Max first principal stress [MPa]
LAM / insertion to tendinous arches	8.9	30.8
Transversus perinei / perineal body	13.7	33.6
Transversus perinei / perineal body	14.7	91.47

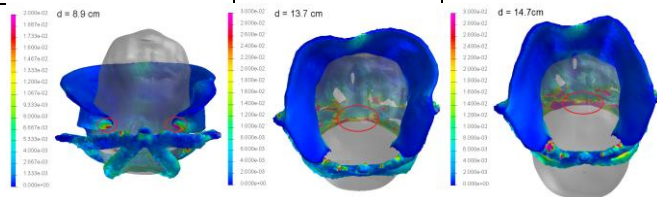


Fig. 7 The first principal stress distribution in the LAM and perineal muscles, d denotes the head station. Red circles mark the LAM attachments to the tendinous arches (left) and the area of perineal body (middle and right).

Concerning the simulation of the FMPP the stress and strain distribution is influenced by the missing subcutaneous structures. These structures are not crucial for the own delivery simulation. Currently they are substituted by appropriate linking elements. Skin deformations shows Fig. 8. Although the acting finger forces are similar, deformations caused by thumb and index finger are much higher than by the middle finger.

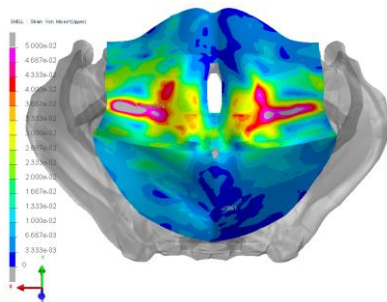


Fig. 8 Strains of the loaded skin. Simulation without delivery.

Differences in the stress distribution of the perineal skin during delivery are shown in Fig. 9. In case of “hands on” the stress moves from the posterior fourchette to the perineal body. The posterior fourchette is a critical place for tearing. The FMPP influences the stress distribution in this critical region.

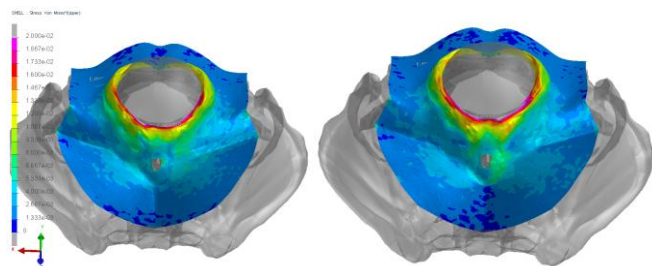


Fig. 9 Comparison of stress distribution in the model with “hands off” (left) and “hand on” (right) technique during delivery.

7. Conclusion

We were able to develop a complex model of the pelvic floor, to simulate the delivery of the fetal head and to simulate the MPP method. The main advantage of this model is that it allows detailed evaluation of individual pelvic floor structures hence increasing the internal validity of our findings and enables extending future applications of the model. Current state of the model enables further applications as the simulation of the manual perineal protection (MPP).

The pilot simulation of MPP shows a weakness of the model, which is the missing connective tissue between the skin and the perineal structure. Although the connective tissue is substituted by linking elements, it should be improved since it would influence the force transmission between perineal structures. Despite that the study confirmed the influence of the fingers pressure on the perineal skin during the vaginal delivery.

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