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# FEATURES OF NUMERICAL SIMULATION OF A STEEL BUILDING STRUCTURE HEATING WITH FIRE PROTECTION BY INTUMESCENT COATING

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## ABSTRACT

*Introduction. The use of modern computer technologies limits high practical and economic results in the construction of modern buildings and structures. This is due to the fact that modern software systems make it possible to predict with sufficient prospects the behavior of building structures under the influence of various factors, including under high-temperature conditions. In relation to the issue of heating steel building structures with fire protection and coatings intumescent under fire conditions, it should be noted that the process of heat and mass transfer in an intumescent coating is currently only partially studied.*

*Objectives. The purpose of the study is the analysis of the application aspects of numerical modeling in the development of the project of fire protection steel constructions using modern software complexes and existing computational and analytical methods, and analyzing critical factors affecting the reliability of the results obtained.*

*Methods. This study investigates the application aspects of numerical modeling in the development of a project for fire protection of steel building structures with intumescent coatings through analysis of existing experimental and theoretical research.*

*Results and discussion. The results of the analysis of the existing experimental and theoretical studies in the field of the application of numerical modeling of heat transfer processes, including in the conditions of high-temperature exposure to fire, showed that the application of numerical modeling in the development of the project of fire protection steel building structures with intumescent coatings is associated with a complex and long process associated with validation Mathematical models of research objects are being developed.*

*Conclusion. The current level of development of numerical modeling technology allows not only to supplement experimental studies, but also, if possible, to greatly reduce them.*

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## 1. INTRODUCTION

Currently, the development of the construction industry is inextricably linked with the use of mathematical modeling, since this approach allows not only to improve the quality of project documentation, but also to reduce the time for its preparation. It should be noted that the existing regulatory framework in Russia for the design of steel building structures has a number of shortcomings associated with its imperfection, and the software used requires updating.

Today, one of the promising directions for achieving the goal of innovative development of functional blocks of the construction industry is the introduction of mathematical modeling, including optimization of the processes of design, construction, operation and disposal of a construction project.

Today, to solve various problems in construction, there are more than 100 software systems (Figure 1) (Fedorova et al., 2017), which are often used together at the design stages and complement each other.

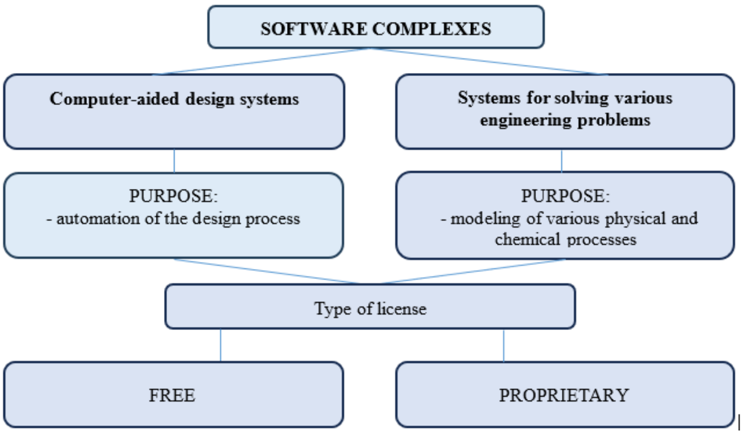


**Figure 1.** Modern software systems

The utilization of software packages often necessitates specific configurations of their modules tailored to the problem at hand, enabling a sufficiently accurate description of the process. This entails not only comprehending the dynamics of the simulated process but also understanding the modeling process itself, as depicted in Figure 2 (See Appendix).

An essential aspect in the design of steel-framed buildings and structures is ensuring their fire resistance, a concern addressed within the framework of developing design documentation for fire protection of steel structures. This developmental process can be delineated into distinct stages (Figure 3), culminating in the selection of appropriate fire protection methods and their respective thicknesses.

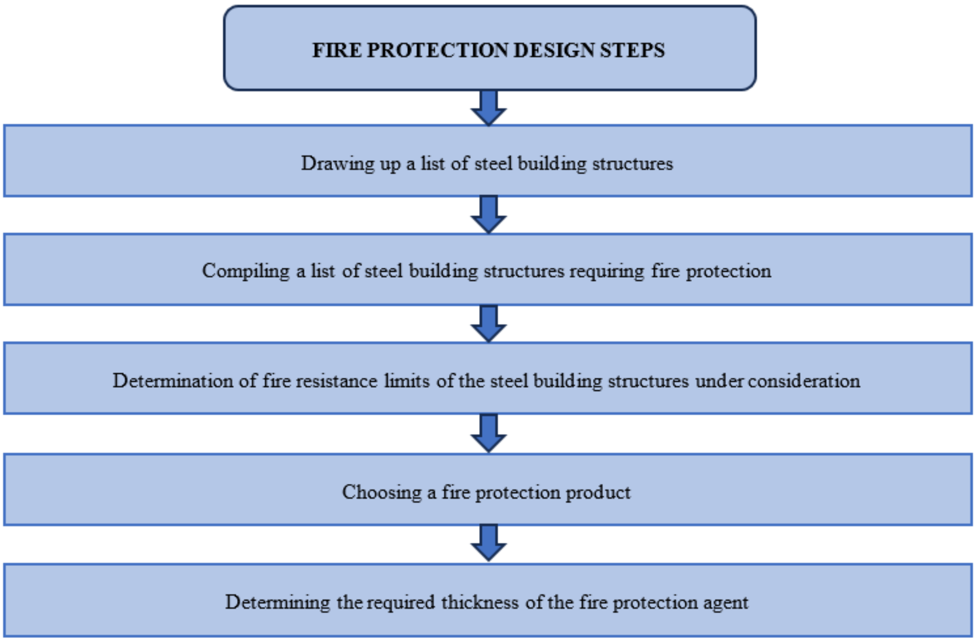


**Figure 3.** Algorithm for designing fire protection of building structures

In recent decades, designers have increasingly opted for intumescent fire-protection coatings in fire protection projects (Golovanov et al., 2014; Pekhotikov et al., 2015; Garlock et al., 2014; Lucherini et al., 2018; Melder et al., 2022; Meshalkin & Boldyan, 2020; Golovina, 2023; Tong et al., 2021; Gatheeshgar et al., 2021). These coatings offer several advantages over traditional methods, including the elimination of the need for special fixtures and devices for attachment to structural surfaces, reduced labor intensity in fire protection tasks, and decreased structural load. Intumescent fire-protection coatings (see Figure 4) stand out as an effective solution for protecting steel building structures.

**Figure 4.** Intumescent fire protecting coating

The effectiveness of an intumescent fire-protecting coating under high-temperature conditions hinges upon its thermophysical properties. Literature reveals (Golovanov et al., 2014; Pekhotikov et al., 2015; Garlock et al., 2014; Lucherini et al., 2018; Melder et al., 2022; Meshalkin & Boldyan, 2020; Golovina, 2023; Tong et al., 2021; Gatheeshgar et al., 2021; Golovanov & Kryuchkov, 2021; Carreras Guzman et al., 2021; Siddiqui et al, 2021; Smith et al., 2019; Li et al., 2021; Morandini et al 2019) that these properties can be influenced by various factors throughout the coating's lifecycle (see Table 1).

**Table 1.** Dependence of the fire-protection efficiency of intumescent fire-protection coatings on various factors and influences

| № | Factors and impacts | The degree of influence on the effectiveness of IFPC | | |
|---|---|---|---|---|
| | | Low | Middle | High |
| | **In laboratory tests** | | | |
| 1 | Application method | + | - | - |
| 2 | Availability of protective and decorative coating | - | + | - |
| 3 | Reduced metal thickness | - | + | - |
| 4 | Coating thickness | - | - | + |
| 5 | Swelling coefficient | - | - | + |
| 6 | Adhesion | - | - | + |
| 7 | Foam coke stability | - | - | + |
| | **Under operating conditions** | | | |
| 8 | Storage and transportation conditions, temperature and humidity operating conditions, shelf life and operation | - | - | + |
| 9 | Fire temperature | - | - | + |

While there is considerable research dedicated to studying the thermophysical properties of various substances and materials, there exists a notable gap in literature concerning the thermophysical characteristics of intumescent coatings and the mathematical modeling of heating for steel structures treated with such coatings (Starkhov et al., 1997; Tsvirkun & Krukovskiy, 2024; Volkov et al., 2009; Zverev et al., 1998; Strakhov et al., 1997; Isakov et al. 1997; Yeremina, 2003). Moreover, existing studies primarily focus on assessing the effectiveness of intumescent coatings under 'standard' temperature conditions. However, recent works (Golovina et al., 2020; Golovanov et al., 2020) delve into evaluating their performance under temperatures associated with hydrocarbon combustion. Additionally, a broader discussion on the efficacy of intumescent coatings under diverse temperature conditions is presented in (Lucherini et al., 2018).

When employing numerical methods to estimate the heating time of a steel building structure treated with intumescent coatings under high-temperature conditions, the primary objective is to determine the temperature distribution ($T$) within the structure over time ($\tau$) and space ($x$, $y$, $z$). This distribution is represented by a function of the form $T = f(x, y, z, \tau)$, derived through solving the Fourier differential heat conduction equation (Equation 1) while considering specific conditions of uniqueness. This mathematical framework encapsulates all the distinctive characteristics of the solution (see Figure 5) (Yudaev, 1998). That is, when determining the temperature field in a structure at any time, it is necessary to solve a boundary value problem for partial differential equations.

$$\partial\frac{\partial T}{\partial \tau} = \alpha\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right), \quad (1)$$

where α is thermal diffusivity (m$^2$/s), determined by equation (2).

$$\alpha = \frac{\lambda}{c\rho}, \quad (2)$$

Where
λ – thermal conductivity (W/(m·K));
c – heat capacity (J/(kg·K));
ρ – density (kg/m3).

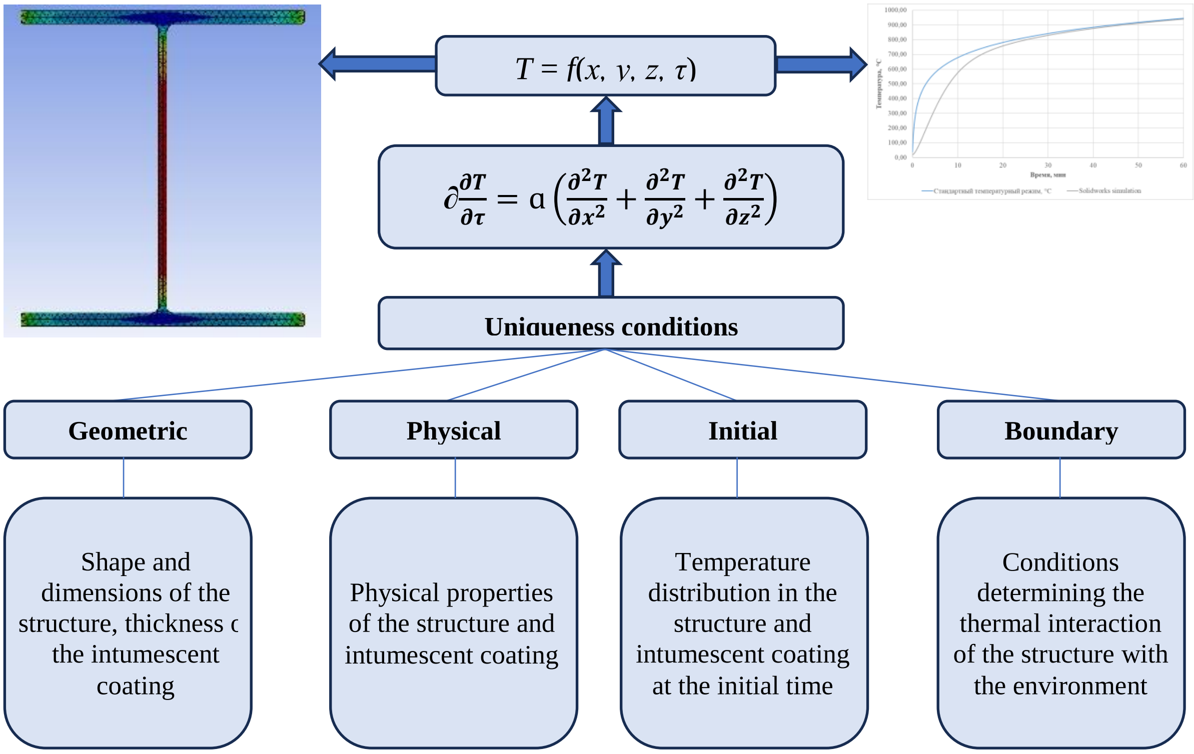


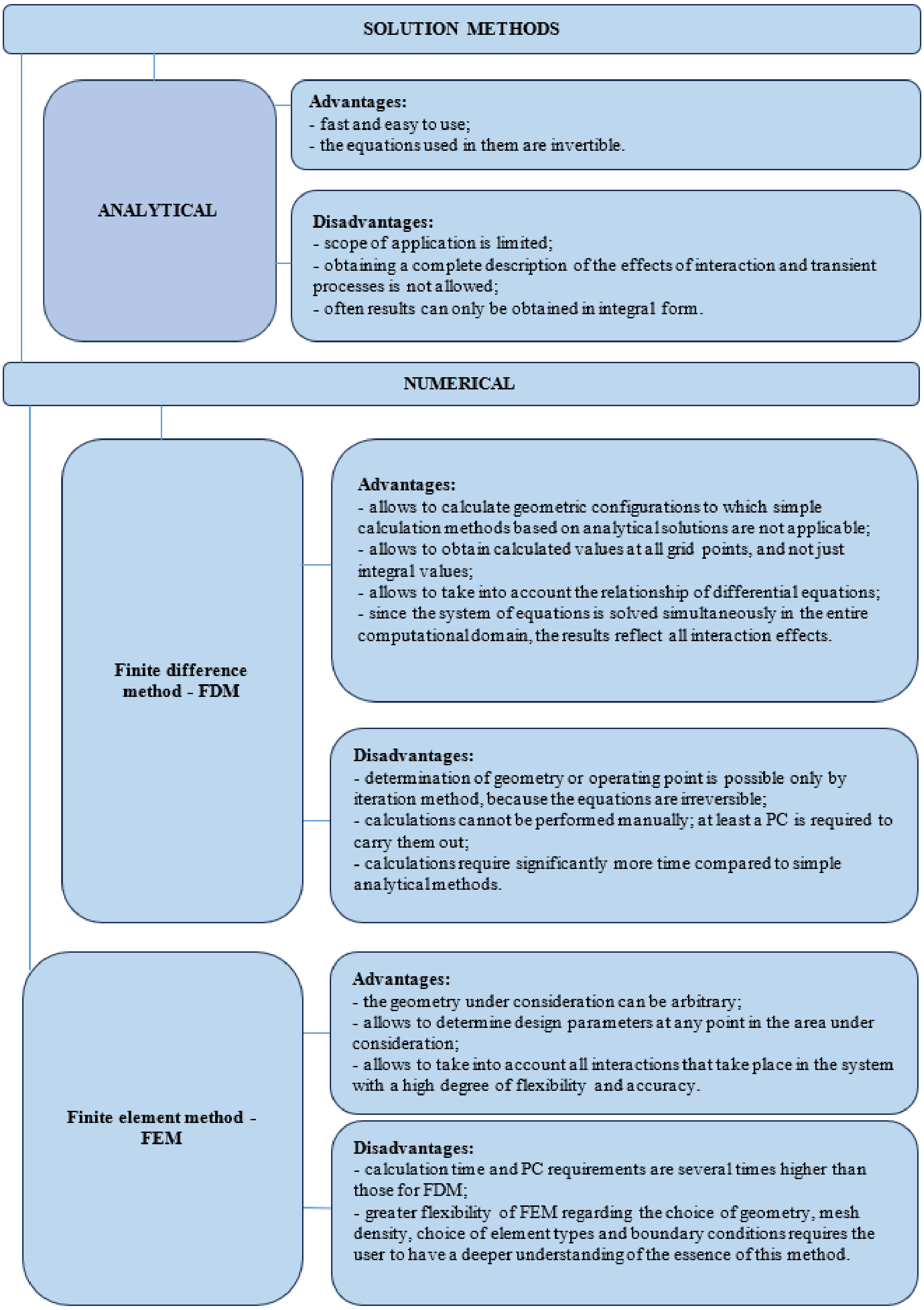
**Figure 5.** Conditions for uniqueness when estimating the heating time of a steel building structure using numerical methods

Among the numerical methods available for solving differential equations, the finite difference method and the finite element method stand out for their widespread use in modern software systems (Kraynov et al., 2016). In numerical modeling, designers often face the task of selecting the most suitable method for solving the differential equations relevant to the process under consideration. The choice depends on factors such as the desired level of accuracy and computational resources. Figure 6 illustrates the advantages and disadvantages of existing numerical and analytical methods.

A comparative analysis reveals that when analytical methods fail to achieve the required level of accuracy, more resource-intensive numerical methods become necessary. For instance, the finite difference method is preferable for structures with simple geometric shapes, while the finite element method is better suited for structures with complex geometries. When employing the finite element method, it is crucial to assess sources of errors inherent in computational models, including input errors, geometric discretization errors, solution discretization errors, time integration errors, and errors in interpreting simulation results.

Additionally, the quality of initial data used in numerical modeling plays a pivotal role, encompassing factors such as geometric dimensions of the structure, thickness of the intumescent coating, thermophysical properties of the steel structure, intumescent coating, and environmental conditions, as well as initial and boundary conditions of heat transfer, and the duration of the simulation process.

While geometric dimensions and thermophysical characteristics of steel building structures are typically straightforward to define for modeling purposes, specifying similar parameters for intumescent fire-protection coatings can present challenges. Obtaining the thermophysical characteristics of such coatings often involves solving the inverse problem of thermal conductivity, wherein input data are derived from fire test results. Attention must be paid to solving this inverse problem, particularly regarding uncertainties in reconstructing various boundary conditions of heat transfer, as the quality of its solution directly impacts subsequent modeling results (Tomachakov & Berezovskaya, 2022).



**Advantages:**
- fast and easy to use;
- the equations used in them are invertible.

**Disadvantages:**
- scope of application is limited;
- obtaining a complete description of the effects of interaction and transient processes is not allowed;
- often results can only be obtained in integral form.

**Advantages:**
- allows to calculate geometric configurations to which simple calculation methods based on analytical solutions are not applicable;
- allows to obtain calculated values at all grid points, and not just integral values;
- allows to take into account the relationship of differential equations;
- since the system of equations is solved simultaneously in the entire computational domain, the results reflect all interaction effects.

**Disadvantages:**
- determination of geometry or operating point is possible only by iteration method, because the equations are irreversible;
- calculations cannot be performed manually; at least a PC is required to carry them out;
- calculations require significantly more time compared to simple analytical methods.

**Advantages:**
- the geometry under consideration can be arbitrary;
- allows to determine design parameters at any point in the area under consideration;
- allows to take into account all interactions that take place in the system with a high degree of flexibility and accuracy.

**Disadvantages:**
- calculation time and PC requirements are several times higher than those for FDM;
- greater flexibility of FEM regarding the choice of geometry, mesh density, choice of element types and boundary conditions requires the user to have a deeper understanding of the essence of this method.

**Figure 6.** Advantages and disadvantages of numerical and analytical methods

While geometric dimensions and thermophysical characteristics of steel building structures are typically straightforward to define for modeling purposes, specifying similar parameters for intumescent fire-protection coatings can present challenges. Obtaining the thermophysical characteristics of such coatings often involves solving the inverse problem of thermal conductivity, wherein input data are derived from fire test results. Attention must be paid to solving this inverse problem, particularly regarding uncertainties in reconstructing various boundary conditions of heat transfer, as the quality of its solution directly impacts subsequent modeling results (Tomachakov ^& Bereyovskaya, 2022).

Assumptions regarding changes in geometric parameters of intumescent coatings during modeling to achieve acceptable solutions under given boundary conditions may not always be evident initially and are refined through comparison with experimental data during the modeling process. Moreover, selecting thermophysical properties of the environment and defining boundary conditions in modeling can also pose difficulties. For example, in assessing compliance of a steel building structure's fire resistance with regulatory requirements, ambient temperature is often assumed to follow a 'standard' regime. The influence of this 'standard' temperature regime is typically specified by a boundary condition of the third kind (Yakovlev, 1988):

- change in the temperature of the medium tв (K) in time τ (s) is given by the following equation (3)

$$T_{\text{в}} = T_i + 345 \cdot lg\left(\frac{8}{60}\tau + 1\right),$$
(3)

- heat transfer coefficient α (W/m$^2$·K) from the medium to the surface of the structure, due to the lack of experimental data, is calculated using formula (4) (Golovanov, 2014)

$$\alpha = 29 + 5{,}77 \cdot s_r \frac{(t_{\text{в}}/100)^4 - (t_0/100)^4}{t_{\text{в}} - t_0},$$
(4)

where $t_0$ is the temperature of the steel building structure, K; $s_r$ – reduced degree of emissivity.

$$s_r = \frac{1}{\left(\frac{1}{s}\right) + \left(\frac{1}{s_0}\right) - 1},$$
(5)

where $s = 0.85$; $s_0$ – degree of emissivity of the surface of a steel building structure.

The modeling of heating for steel building structures protected by intumescent coatings under fire conditions is currently challenging due to insufficient study of the heat transfer coefficient from the fire environment to the steel structure (Yakovlev, 1973). The initial temperatures of the structure ($T_i$) and the environment ($T_B$) are typically assumed to be 293 K. However, accurately modeling the heat transfer process necessitates knowledge of this coefficient. Existing scientific data on the heat transfer coefficient are limited, as depicted in Figure 7.

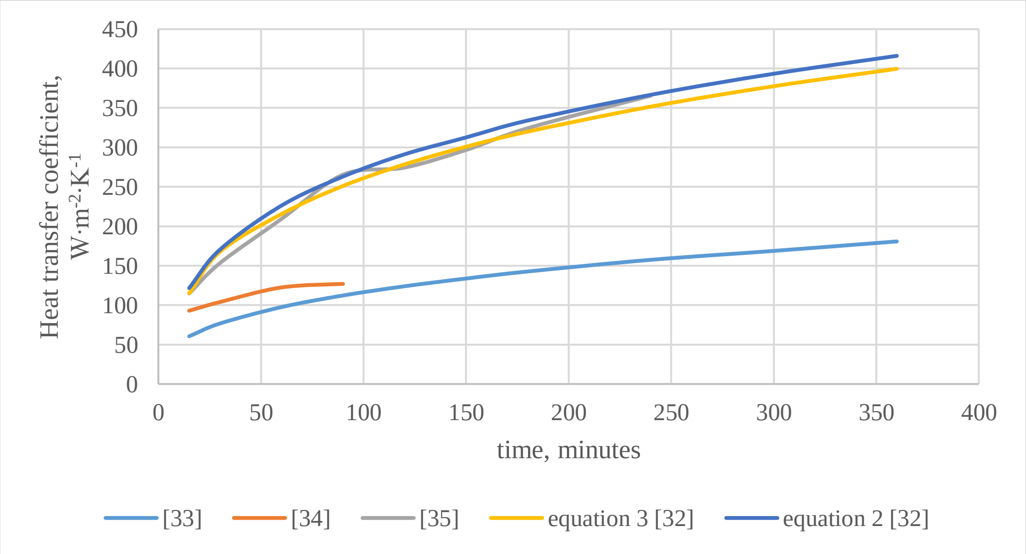


Figure 7. Heat transfer coefficient (‘standard’ temperature regime)

The temperature conditions during a fire event often deviate significantly from the 'standard' regime (Minaylov, 2020; Perera et al., 2021; Johnston et al., 2021; de Silva et al., 2022; Zhang et al., 2014; de Silva, 2020; Zhang et al, 2014; Ministero dell’Interno—Dipartimento dei Vigili del Fuoco, del Soccorso Pubblico e Della Difesa Civile, 2020), making it impossible to conduct numerical modeling without additional experimental and theoretical studies to ascertain the heat transfer coefficient. Moreover, it's crucial to acknowledge that the thermophysical characteristics of intumescent coatings are notably affected by the magnitude of heat flow, with varying effects observed under different temperature conditions (Eremina & Minaylov, 2023; Beh et al., 2020; Lucherini & Maluk, 2019; American Coating Association, 2022; Morandini et al., 2019)

## 4. CONCLUSION

In contemporary building design, numerical modeling of physical processes is extensively utilized to address various challenges, including the heating of steel structures under high-temperature conditions. The rationale behind the growing reliance on numerical modeling for solving thermotechnical problems in steel building structures with intumescent coatings lies in several advantages it offers over physical experimentation.

Transitioning to numerical modeling requires preliminary experimental studies on steel structures treated with intumescent coatings under diverse temperature conditions, followed by the validation of developed mathematical models. Furthermore, establishing a regulatory framework to govern the application of results obtained through numerical modeling is imperative. Accreditation of computational laboratories is also crucial, as the proficiency of the software users significantly influences the accuracy and reliability of the results.

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## Appendix:

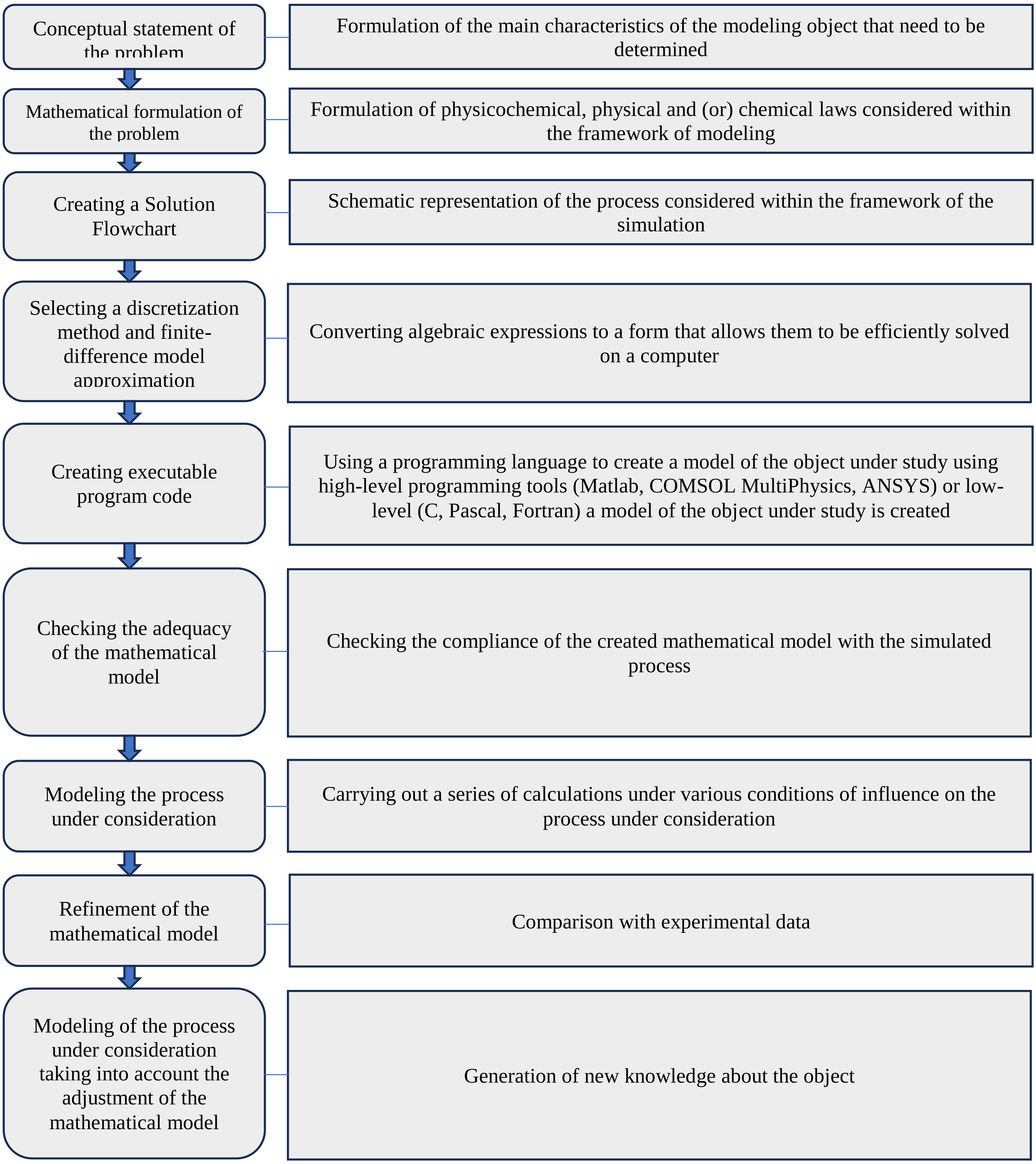

**Figure 2**. Sequence of computer modeling (Ankudinov et al., 2014)