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Preliminary Design Evaluation of Solid-Propellant Rocket Engines

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Purpose. This article raises the issue of the necessity to develop methods for automated design evaluation of solid-propellant rocket engines at the early stages of missile development. **Design / Method / Approach**. The study is based on analytical models and empirical data derived from the development of numerous SREs by design bureaus, particularly Yuzhnoye State Design Office. It uses parametric analysis and optimization techniques, supported by statistical correction and verification against real-world motor data **Findings**. The article identifies critical parameters that influence solid-propellant rocket engines (SRE) efficiency and offers a computational framework for optimizing these parameters. The methodology significantly reduces the time required for preliminary assessments and allows for automated exploration of design alternatives. **Theoretical Implications**. This study contributes to the theoretical understanding of SRE performance modeling and optimization during conceptual design. It outlines how analytical dependencies can be constructed and refined based on engineering theory and empirical calibration. **Practical Implications**. The developed approach enables engineers to quickly generate and evaluate multiple engine design scenarios, improving the quality and speed of early decision-making in missile system development. **Originality / Value**. The work offers a practical and validated methodology for automated design evaluation of SREs, filling a gap in the early-stage engineering workflow. It is valuable to aerospace engineers, defense researchers, and developers of propulsion systems. **Research Limitations / Future Research**. The methodology focuses on typical SRE configurations and assumes statistical consistency across historical data. Future research may expand the models to incorporate novel materials, 3D-printed components, and adaptive control systems. **Article Type**. Methodological paper.

Keywords:

solid propellant rocket engines, automated design evaluation, preliminary design stage, parametric optimization, analytical performance modeling

Мета. У цій статті підіймається питання необхідності розробки методів автоматизованої проєктної оцінки твердопаливних ракетних двигунів на ранніх етапах розробки ракетних комплексів. **Дизайн / Метод / Підхід**. Дослідження базується на аналітичних моделях та емпіричних даних, отриманих під час розробки численних твердопаливних ракетних двигунів (ТРД) конструкторськими бюро, зокрема ДП «КБ «Південне». Застосовано методи параметричного аналізу та оптимізації з подальшою статистичною корекцією та перевіркою на основі реальних даних двигунів. **Результати**. У статті визначено ключові параметри, що впливають на ефективність ТРД, та запропоновано обчислювальну структуру для їх оптимізації. Методика суттєво скорочує час, необхідний для попередньої оцінки, та дозволяє автоматизувати дослідження альтернативних варіантів конструкції. **Теоретичне значення**. Це дослідження сприяє розвитку теоретичного розуміння моделювання та оптимізації характеристик ТРД на концептуальному етапі. Показано, як аналітичні залежності можуть бути побудовані та уточнені на основі інженерної теорії та емпіричного калібрування. **Практичне значення**. Розроблений підхід дозволяє інженерам швидко формувати та оцінювати декілька варіантів конструкції двигунів, підвищуючи якість і швидкість прийняття рішень на ранніх етапах створення ракетних систем. **Оригінальність / Цінність**. Робота пропонує практичну та верифіковану методику автоматизованої оцінки проєктних рішень для ТРД, що заповнює прогалину в процесі раннього інженерного проєктування. Вона є цінним ресурсом для аерокосмічних інженерів, фахівців з оборонних технологій і розробників рушійних установок. **Обмеження дослідження / Майбутні дослідження**. Методика орієнтована на типові конфігурації ТРД і базується на припущенні статистичної узгодженості історичних даних. У майбутньому дослідження можуть бути розширені з урахуванням нових матеріалів, компонентів, виготовлених на 3D-принтерах, і адаптивних систем управління. **Тип статті**. Методологічна стаття.

Ключові слова:

твердопаливні ракетні двигуни, автоматизована проєктна оцінка, етап початкового проєктування, параметрична оптимізація, аналітичне моделювання характеристик

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Solid-propellant rocket engines (SREs) play a fundamental role in the design and performance of modern missile systems. Their effectiveness directly impacts the range, payload capacity, stability, and overall success of the vehicle in achieving mission objectives. However, the process of designing and evaluating SREs remains complex and time-consuming, often requiring the involvement of multiple domain-specific experts in propulsion, thermodynamics, internal ballistics, structural integrity, and materials engineering. This challenge becomes particularly acute during the preliminary design stage, when multiple configuration options must be rapidly evaluated under time and resource constraints (Glazkov et al., 2018). To address this problem, an automated methodology has been developed for the rapid assessment of key performance parameters of SREs used in missile systems. This approach enables engineers to conduct computational evaluations of dozens or even hundreds of design options without the need for full-scale calculations or consultations with specialized departments. The proposed methodology is built upon a combination of analytical models, empirical correlations, and statistical data obtained from previously developed SREs. The system is designed for application in a wide range of missile classes - from tactical and operational-tactical missiles to intercontinental ballistic missiles and space launch vehicles. It allows the user to determine optimal design parameters such as fuel mass, motor diameter, chamber pressure, nozzle expansion ratio, and burn time under given constraints. The methodology significantly accelerates the conceptual design process by replacing labor-intensive manual calculations with instant, software-driven evaluations.

This paper presents the theoretical foundations, structure, and implementation of the automated evaluation methodology, as well as its validation through comparisons with real-world designs. It also explores the applicability of the method to various SRE configurations and outlines its practical value for engineers engaged in early-stage missile development projects.

Purpose

The purpose of this study is to develop and present an automated methodology for evaluating the key performance parameters of SREs during the early stages of missile system design. The work aims to streamline the process of preliminary assessment by reducing reliance on manual calculations and minimizing the need for consultations with multiple domain experts. Through the integration of analytical models, statistical data, and design experience, the proposed approach enables rapid exploration of multiple SRE configurations under given technical and operational constraints.

This methodology is intended to assist engineers and designers in selecting optimal motor parameters - such as propellant mass, chamber pressure, burn time, and nozzle expansion ratio - that maximize overall missile efficiency according to ballistic, dimensional, mass, and reliability criteria. It also supports the identification of trade-offs and limitations that arise during configuration selection. The study emphasizes the need for fast and reliable tools that can support high-quality decision-making at the conceptual stage of missile development.

Data and Methods

The development of the automated evaluation methodology is based on a combination of theoretical models, empirical data, and statistical analysis of previously developed SREs. The primary data sources include engineering documentation, performance archives, and statistical datasets from missile development projects carried out by Yuzhnoye State Design Office and other aerospace institutions (Kirichenko et al., 2016).

The methodology integrates the following key elements:

1. *Analytical Modeling*. Fundamental equations from internal ballistics, thermodynamics, structural mechanics, and gas dynamics were used to describe the core physical processes within SREs. These models serve as the backbone for calculating performance metrics such as chamber pressure, specific impulse, and structural loads.

2. *Empirical Correlation*. Analytical results are refined using empirical correction factors derived from historical test data and operational experience. These corrections enhance the reliability of predictions across a wide range of design cases.

3. *Effectiveness Assessment*. The effectiveness of precision strikes was assessed by examining the precision, speed, and impact of multiple launch rocket systems in various combat scenarios, using available data and reports on their use in military engagements.

4. *Literature Review*. A review of open-source publications, technical documents, and scientific research on the development, deployment, and operational use of HIMARS and similar systems in combat (Bondarenko et al., 2024).

5. *Data Synthesis*. Data gathered from military reports, news articles, and technical studies were synthesized to draw conclusions about the strategic and operational implications of multiple launch rocket systems in modern warfare.

Background and Motivation

The design of SREs for missile systems is a highly complex engineering task. It involves the simultaneous consideration of numerous parameters, including internal ballistics, thermal regimes, structural integrity, and aerodynamic performance. Traditionally, this process requires the involvement of a large number of specialists across multiple disciplines and consumes considerable time and resources, especially during the conceptual phase of development.

At the early stages of missile design, engineers are often tasked with evaluating a wide range of possible configurations for SRMs under tight time constraints. The ability to rapidly assess the performance of dozens or even hundreds of variants become critical to the overall efficiency of the design process. In such cases, traditional calculation methods become inefficient, and the lack of automation leads to delays and decision-making bottlenecks.

The need for a fast, reliable, and reasonably accurate solution prompted the development of an automated methodology capable of providing preliminary assessments of SRM performance on a personal computer. This methodology is specifically intended to support design decisions during the initial project phases, where rough but informative estimations can significantly influence the direction of further engineering work. By automating the estimation of key parameters - such as thrust, chamber pressure, burn time, and motor geometry - this approach allows a single engineer to perform complex analyses in a fraction of the time required by manual or segmented workflows. The methodology presented here is based on practical experience accumulated during the development of numerous SREs by Yuzhnoye State Design Office (Ukraine) and is supported by verified empirical and statistical data collected over several decades (Kirichenko et al., 2014).

Literature Review

As part of the present work, an analysis and systematic review of recent publications directly and indirectly related to the preliminary design evaluation and development of solid-propellant rocket engines was carried out. The review covered both classical and applied studies of internal ballistics and structural design, as well as contemporary numerical and experimental investigations – for example, studies on internal ballistics and mathematical modelling of combustion processes (Kositsyna et al., 2021; Tian et al., 2021; Rashkovskiy & Yakush, 2020), investigations of nozzle insert erosion and behaviour (Cang & Wang, 2024; Almayas et al., 2021), numerical studies of ignition/transient processes and gas dynamics of combustion products (Wentao et al., 2024; Deyou et al., 2024), and works on grain regression modelling, mesoscale descriptions of AP/HTPB combustion, and grain-shape optimization (Rashkovskiy et al., 2020; Combustion & Flame, 2023; Li et al., 2024). Studies addressing the energetic characteristics of propellant components and thermal protection materials were also examined (Wang et al., 2025; Mochonov et al., 2020).

Despite the availability of modern publications from 2020 – 2025, the review indicates that methodologies are dispersed across multiple approaches – experiments, numerical simulation, empirical correlations, and materials science studies – with individual works typically addressing only specific aspects (e.g., nozzle erosion or mesoscale combustion) rather than providing a comprehensive solution for the preliminary design evaluation of a propulsion system as an integrated case (Galletly & Verstraete, 2025; Teng et al., 2025). The objective of this paper is therefore to raise the issue of creating a unified algorithm: to collect diverse cases and methods from recent literature, to synthesize empirical relationships and numerical approaches, and to combine them into a single, reproducible methodology for the preliminary design evaluation of solid-propellant rocket engines that closes identified gaps and improves the reproducibility and accuracy of calculations (Chen et al., 2024).

Structure of the Automated Evaluation Methodology

The proposed methodology is designed to estimate the key parameters of SREs at the conceptual design stage using a combination of analytical models, empirical corrections, and optimization algorithms. Its structure reflects the interconnected nature of rocket design, where performance, geometry, and manufacturing constraints must be considered simultaneously. The methodology comprises the following main components.

Input Data and Design Variables

The evaluation begins with the input of baseline design parameters, including: motor diameter (D); propellant mass (ω); chamber pressure (P_k); nozzle expansion ratio (ζ); burn time (t_p). These parameters are treated as variable within defined ranges based on the target missile class. Additionally, constraints related to maximum diameter, integration volumes, and separation conditions are considered (Bondarenko & Habrinets, 2023).

Optimization Criteria

The methodology allows optimization according to several possible criteria, including: external ballistics (e.g., maximizing range or payload mass); mass efficiency (e.g., minimizing launch mass); dimensional constraints (e.g., minimizing length or diameter); reliability and safety; economic or manufacturing feasibility; multiple criteria can be combined using weighting factors or applied in stages.

Analytical Models and Dependencies

Each SRE parameter is calculated using core equations derived from the theory of internal ballistics, thermodynamics, structural mechanics, and empirical design practice. Key performance characteristics include: specific impulse in vacuum (I_{sp}); maximum chamber pressure ($P_k$max); propellant mass flow rate ($\dot{m}$); nozzle throat erosion (Δd_t); total motor length and structural mass. The models are corrected using statistical data from legacy SRE designs developed by Yuzhnoye SDO and other aerospace institutions. These corrections ensure applicability across a wide design space and improve prediction reliability (Ushkin, 2016).

Design Constraints and Feasibility Checks

The tool checks whether selected configurations are feasible given geometric limitations, required performance levels, and production capabilities. For example, the method accounts for: constraints on the combustion rate and chamber pressure for safe stage separation; compatibility with available nozzle and casing technologies; integration requirements with launch platforms.

Output and Interpretation

The methodology produces a full set of output parameters for each configuration, including: thrust curve and impulse; pressure-time history; mass breakdown (propellant, structure, nozzle); dimensional layout; thermal and structural load estimates. These outputs support rapid decision-making and allow comparison across multiple variants, enabling the identification of optimal configurations.

Parameter Ranges and Application Domains

The automated evaluation methodology has been developed to support a broad spectrum of SRM configurations used in various classes of missile systems. These range from tactical and operational-tactical missiles to intercontinental ballistic missiles (ICBMs) and space launch vehicles. To ensure versatility and applicability, the methodology incorporates parameter ranges representative of real-world engineering practice (Bondarenko et al., 2025).

Tactical and Operational-Tactical Missiles

For short- and medium-range missile systems, the methodology supports the following parameter ranges: motor diameter 0.25–0.9 m; propellant mass 150–4500 kg; chamber pressure 3.9–14.7 MPa; burn time 10–50 s; nozzle expansion ratio: 2.5–10.

A typical SRM for such missiles is shown on Fig. 1. Key features of this SRM: composite propellant; propellant charge is bonded to the motor casing; the casing is made of high-strength steel; fixed nozzle. These motors are typically designed with stationary nozzles, composite solid propellants, and steel casings. Their configurations emphasize compactness, reliability, and ease of integration into mobile launch platforms.

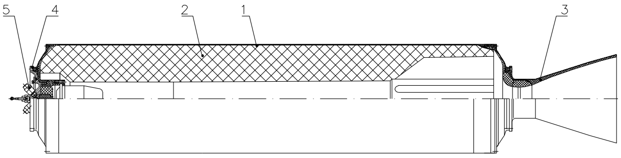

Figure 1 – SRM design scheme: 1 - motor casing, 2 - structurally-bonded solid propellant grain, 3 - nozzle assembly, 4 - forward dome, 5 - ignition system (Source: Authors)

Intercontinental Ballistic Missiles and Space Launch Missiles

For large-scale propulsion systems, the methodology accommodates extended ranges of input parameters: motor diameter 0.9–2.5 m; propellant mass 2100–65000 kg; chamber pressure 3.92–11.77 MPa; burn time 10–100 s; nozzle expansion ratio: 2–10.

These motors often feature composite or wound plastic casings (cocoon-type), bonded grain designs, and movable nozzles for thrust vector control using hydraulic or electric actuators.

Modular Applicability

The structure of the methodology allows it to be adapted to other classes of SRMs with minimal modification. This includes: upper stages with lower thrust and longer burn durations; launch boosters requiring high-thrust, short-duration performance; experimental configurations with novel grain geometries or additive-manufactured components.

The system is thus applicable at multiple stages of the development pipeline – from conceptual studies to early-stage trade-off analysis – and can be customized to match the evolving needs of missile programs.

Analytical Models and Statistical Calibration

The core of the automated evaluation methodology is built upon a series of analytical models describing the thermodynamic, ballistic, and structural behavior of SRMs. These models are augmented with statistical corrections derived from empirical data obtained through the development and testing of multiple SRM configurations, primarily at Yuzhnoye State Design Office (Ushkin et al., 2016).

Energy Performance Models

The specific impulse in vacuum (I_{sp}–vac) is a fundamental metric for evaluating propulsion efficiency. In this methodology, the ideal thermodynamic impulse is modeled as a function of nozzle expansion ratio (ζ) and chamber pressure (P_k), calibrated for various propellant formulations:

$$I_{sp}^{ideal} = f(\zeta, P_k). \quad (1)$$

Losses due to nozzle efficiency, flow separation, and erosion are introduced via empirical correction terms, yielding a realistic prediction of the effective specific impulse:

$$I_{sp}^{real} = I_{sp}^{ideal} - \Delta I_{losses}. \quad (2)$$

Parameters such as aluminum content (q_m), throat-to-exit area ratio, and nozzle contour length are also accounted for, especially when assessing high-performance composite propellants.

Internal Ballistic Models

The internal ballistic behavior of SRMs is a key factor in determining pressure stability, thrust generation, and structural loading. In the proposed methodology, chamber pressure is estimated under nominal and off-nominal conditions using analytical relationships supplemented with statistically derived correction factors.

The baseline chamber pressure P_k is treated as a design input, reflecting mission-specific requirements. However, due to variations in geometry, temperature, and burn rate characteristics, the actual maximum pressure P_k^{max} may exceed this nominal value.

To estimate P_k^{max}, a multi-parameter expression is used:

$$P_k^{max} = P_k \cdot f(\Delta S, \nu, \alpha_t, \Delta T, \delta_{sl}, \Delta u), \quad (3)$$

where ΔS – maximum deviation of the burning surface, m^2; ν – pressure exponent in the burn rate law, dimensionless; α_t – temperature sensitivity coefficient, 1/K; ΔT – operational temperature deviation, K; δ_{sl}, Δu – statistical factors reflecting real-world variability, dimensionless. These parameters capture both design-driven and environmental variations influencing pressure buildup during operation.

When geometric characteristics of the grain are known, the deviation ΔS_{max} can be approximated as a function of grain elongation λ_z. The following empirical formula, based on regression analysis of design data, is applied:

$$\Delta S_{max} = -0.0055 \cdot \lambda_z^2 \cdot 0.1387 \cdot \lambda_z + 8.5875 . \quad (4)$$

This expression reflects typical surface variation behavior in bonded charge configurations and provides a reliable estimate of the expected maximum deviation.

When the grain geometry is not yet defined and λ_z is unavailable, a simplified expression can be used to estimate the peak chamber pressure based on material characteristics and environmental conditions:

$$P_k^{max} = P_k^{nom} \cdot \frac{0.0044 \cdot \alpha_t \cdot \Delta T + 1.1}{\sqrt{1-\upsilon}} . \quad (5)$$

This formula enables designers to assess pressure risk early in the conceptual design process using only propellant data and environmental temperature deviation.

Erosion and Throat Regression Models

Throat erosion is a critical factor affecting chamber pressure and burn stability, especially in motors using carbon-carbon throat inserts. A dedicated empirical model calculates erosion (Δd_t) as a function of time, propellant gas aggressiveness, and throat material density:

$$\Delta d_t = k_1 \cdot k_2 \frac{P_k^{n1} \cdot P_k^{n2} \cdot \varphi \cdot \tau}{\rho} , \quad (6)$$

where τ – burn time, s; φ – oxidizer potential, dimensionless; ρ – insert material density, $kg \cdot m^3$; P_k – chamber pressure and temperature, Pa. This model helps assess nozzle throat durability and stability during long-duration burns.

Structural Mass and Component Weight Models

Mass estimation models are tailored to the specific geometric and structural characteristics of SRM components. While basic formulas rely on volume and material density, correction factors are introduced for: mounting interfaces (e.g., flanges, bulkhead fittings); launch system integration structures; reinforced sections subject to high stress. For example, mass estimates for forward hatches or nozzle mounting rings are adjusted based on empirical deviations observed during manufacturing (AbdelGawad & Guozhu, 2022).

Statistical Calibration and Validation

All models are calibrated using legacy datasets derived from the design and testing of real SRMs. The comparison of predicted versus actual parameters showed deviation ranges of structural mass from – 1.8% to + 3%; specific impulse from – 0.15% to – 0.3%; overall motor length from – 1.8% to + 3.2%.

These margins confirm that the analytical models, when properly calibrated, can provide reliable approximations suitable for the preliminary design phase.

Algorithmic Implementation and Calculation Workflow

The proposed methodology has been implemented as a structured calculation tool that enables rapid evaluation of various SRM configurations on a standard personal computer. The core objective of the implementation is to provide engineers with a fast, flexible, and user-friendly system that facilitates early-stage decision-making without compromising accuracy.

Software Platform and Tools

The methodology was originally implemented using Microsoft Excel combined with custom macros and formula libraries. This environment was selected for its accessibility, ease of use, and support for parametric tabulation, graphical analysis, and modular design logic. The tool can be extended or ported to more advanced platforms (e.g., Python or MATLAB) if integration with external simulation packages is needed.

Input Interface

Users begin by entering or selecting required mission parameters (e.g., payload mass, flight duration); initial geometric constraints (motor length, diameter limits); ranges for design variables (pressure, burn time, expansion ratio); optimization criteria (e.g., mass minimization, performance maximization). The interface also includes default material properties, propellant characteristics, and empirical correction coefficients, which can be adjusted if custom data is available.

Calculation Logic and Workflow

The computational core proceeds through the following steps. (1) Initialization: Set up design space grid based on variable ranges. (2) Geometry Estimation: Calculate internal motor volume, charge shape factor, nozzle dimensions. (3) Internal Ballistic Simulation: Estimate chamber pressure, propellant mass flow rate, burn duration, and thrust profile. (4) Thermodynamic Analysis: Compute specific impulse, temperature, and exhaust parameters. (5) Structural Assessment: Estimate motor casing mass, thermal loads, and stress factors. (6) Erosion Model: Apply throat regression model to check nozzle stability. (7) Feasibility Check: Evaluate constraint violations (e.g., overstress, integration limits). (8) Result Compilation: Store all outputs for analysis and ranking. Each configuration is processed automatically, and results are stored in tabular form for batch comparison.

Output Visualization

The system includes basic visualization tools to plot thrust vs. time profiles; compare mass and performance trade-offs across design variants; highlight constraint-violating configurations; generate summary charts for engineering reports or presentations.

Performance

On a typical desktop system, the tool can evaluate hundreds of configurations in minutes. This enables fast iteration and supports design optimization loops without requiring high-performance computing resources.

The Mathematical model of an SRM

An SRM mathematical model is an abstract, formally defined representation suitable for analysis via mathematical methods and simulation. It replaces the real engine and its behavior with a collection of elementary subprocesses of different physical character. During design, emphasis is placed on processes that affect flight conditions, thrust output, propellant consumption, mass and energy balances, performance efficiency, and related parameters (Senkin & Syutkina-Doronina, 2019).

To formulate the model mathematically, we adopt a block-based approach in which each block encapsulates a set of equations describing an elementary subprocess within the system. The SRM design model is composed of the following blocks: geometrical block; mass block; ballistic block; energy block; structural (strength) block.

Individual equation groups are assembled into a single system that constitutes the mathematical description of the SRM (Oglykh et al., 2010). This mathematical model is then translated into specialized algorithms for computer simulation of the engine's operational processes. The model and associated simulation algorithms form the basis for methodological and software instruments used in optimization at early design stages and for determining the SRM's principal characteristics. The complete SRM mathematical model, built according to a block-based methodology, includes the following components: block for determining the energy characteristics of the SRM; block for determining the dimensional (geometrical) characteristics of the SRM; block for determining the mass characteristics of the SRM. Figure 2 shows a schematic diagram of the SRM mathematical model.

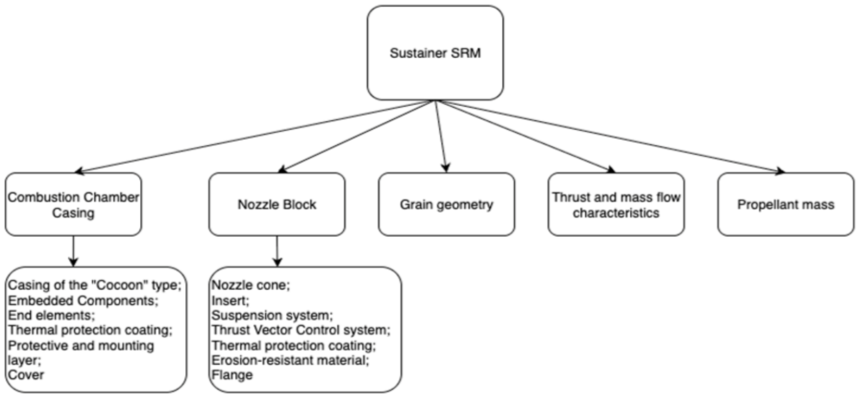

Figure 2 – Schematic diagram of the SRM mathematical model (Source: Authors)

As an illustrative example, this section presents a mathematical model describing the dimensional and mass characteristics of the SRM. The dimensional and mass characteristics of the solid-propellant tactical missile (SPTM) encompass the overall dimensions and mass properties of the motor itself, as well as its principal subsystems and components. These characteristics are determined from the values of key design parameters, input data, and the SRM's structural-layout configuration. The SRM of an operational-tactical missile must satisfy the optimal requirements for its structural configuration. To achieve the designated performance objectives, the design must employ lightweight yet durable casing, ensuring a maximal structural mass fraction, defined as:

$$\alpha = \frac{M_{str}}{M_{prop}}, \tag{7}$$

where M_{str} – structural mass, kg; M_{prop} – propellant mass, kg. Additionally, the system must incorporate a nozzle block with thrust vector control components, ensuring the complete execution of the prescribed flight program. The overall length of the SPTM, L_{SPTM}, is calculated using the following relation:

$$L_{SPTM}(\bar{p},\bar{x}) = L_{WSL} + L_{SRM}(\bar{p},\bar{x}) + L_{UML} \tag{8}$$

where $\bar{p}$ – vector of SPTM parameters to be optimized; $\bar{x}$ – input data vector; L_{WSL} – length of the warhead section of the SPTM, m; L_{SPRM} – length of the sustainer SRM, m; L_{UML} – unaccounted length of the SPTM, m.

Under constraints on the maximum allowable length and design parameters of the SPTM, the initial mass $m_0(\bar{p},\bar{x})$ can be determined by solving the following transcendental equation:

$$L_{SPTM}(\bar{p},\bar{x},m_0) = L_{SPTM}^{lim}, \tag{9}$$

where L_{SPTM}^{lim} – limit on the total length of the SPTM, m.

The payload mass, m_{pl}, is defined as the total mass of the warhead section, encompassing the mass properties of all constituent elements and subsystems. It is assumed that m_{pl} includes the mass of the SPTM flight control system instrumentation, as well as the complete set of countermeasures for missile defense penetration. Taking these factors into account, the mass of the warhead section, m_{pl}, can be determined using the following relation:

$$m_{pl} = m_0 - \lfloor m_{SPRM}(\bar{p},\bar{x}) + m_{IS}(\bar{p},\bar{x}) + m_{TS}(\bar{p},\bar{x}) + m_u \rfloor \tag{10}$$

where m_{IS}, m_{TS} – masses of the transition and tail sections, kg; m_{SPRM} – mass of the sustainer SPRM, kg; m_u – unaccounted masses of elements and subsystems, whose calculations are not performed within the algorithm for determining the main characteristics of the SPTM, kg (Sforzini, 1972).

The masses of the transition and tail sections are determined by the following relations

$$m_{IS} = \pi \cdot \rho_{md} \cdot L_{IS} \cdot \delta_{eqt} \cdot (2 \cdot R_{ex} - \delta_{eqt}) \tag{11}$$

$$m_{TS} = \pi \cdot \rho_{md} \cdot L_{TS} \cdot \delta_{eqt} \cdot (2 \cdot R_{ex} - \delta_{eqt}) \tag{12}$$

where ρ_{md} – density of the material used for manufacturing the sections, $kg \cdot m^3$; L_{IS}, L_{TS} – lengths of the transition and tail sections, respectively, m; R_{ex} – external radius of the cylindrical part of the SPRM combustion chamber, m; δ_{eqt} – equivalent thickness of the nominally smooth shell of the sections, m.

For axial compressive loading, the equivalent thickness of a nominally smooth shell produced by chemical etching is determined by the following relation:

$$\delta_{eqt} = 1.78 \cdot \sqrt{\frac{F_{AxC}}{2\cdot\pi\cdot K_{st}\cdot E\cdot(\psi+0.2)}} \tag{13}$$

where K_{st} – stability coefficient under axial compressive loading, dimensionless. $K_{st} = 0.28 \div 0.34$; E – Young's modulus of elasticity, Pa(N·m^{-2}); ψ – reinforcement efficiency factor, dimensionless; F_{AxC} – axial compressive force, N.

If the shell is manufactured by mechanical milling, the equivalent thickness δ_{eqt} is determined by the following relation:

$$\delta_{eqt} = 1.48 \cdot \sqrt{\frac{F_{AxC}}{2\cdot\pi\cdot K_{st}\cdot E\cdot(\psi-0.25)}} \tag{14}$$

The reinforcement efficiency factor ψ, in the case when the primary load is axial compression and the shell is manufactured by chemical etching, is determined by the following relation:

$$\psi = 14.4 \cdot \frac{(R_{ex}\cdot\sigma_t)^2}{K_{st}\cdot E\cdot F_{AxC}} \tag{15}$$

where σ_t – ultimate strength of the material used for manufacturing the sections, Pa(N·m^{-2}). If the shell is manufactured by mechanical milling, the reinforcement efficiency factor ψ is determined by the following relation:

$$\psi = 9.9 \cdot \frac{(R_{ex}\cdot\sigma_t)^2}{K_{st}\cdot E\cdot F_{AxC}} \tag{16}$$

The calculated value of the axial compressive force F_{AxC} is determined by the following relation:

$$F_{AxC} = \gamma \cdot F \tag{17}$$

where F – operational compressive force acting on the section, N; γ – safety factor, dimensionless. The length of the tail section L_{TS} is determined by the following relation

$$L_{TS} = h_{RH} - L_{NB} \cdot \frac{1-\eta}{1+n_{fn}} - L_{rec} \tag{18}$$

where h_{RH} – height of the rear dome of the sustainer SRM combustion chamber, m; L_{NB} – length of the engine nozzle block, m; η – degree of nozzle block embedding into the combustion chamber, dimensionless; n_{fn} – number of folds in the nozzle part not embedded in the combustion chamber, dimensionless; L_{rec} – length of the part of the rear end component not contacting the combustion chamber casing, m (Oyedeko & Egwenu, 2021).

Advantages and Limitations

The automated evaluation methodology for SRMs offers significant benefits for early-stage missile system design. At the same time, its application scope is defined by the assumptions, simplifications, and data sources embedded in the model (Hashish, 2018). This section outlines both the strengths and constraints of the approach.

Advantages

1. *Rapid Evaluation of Multiple Configurations*. The methodology enables engineers to analyze dozens or even hundreds of

SRM design variants in a matter of minutes. This significantly accelerates trade-off studies and supports agile decision-making during concept selection.

2. *Reduced Dependence on Specialized Experts*. By incorporating essential calculation models and calibrated empirical data, the system allows a single engineer to conduct comprehensive assessments without relying on multiple domain specialists in ballistics, thermodynamics, or structural mechanics.

3. *Built-In Optimization and Constraint Handling*. The methodology supports the definition of performance criteria (e.g., range, efficiency, structural mass) and geometric or operational constraints. Infeasible solutions are automatically filtered out, ensuring the practicality of design options.

4. *Adaptability Across Missile Classes*. The modular design of the tool allows its application to various classes of rockets – from short-range tactical systems to ICBMs and launch vehicles – by simply adjusting input parameter ranges and performance targets.

5. *Statistically Calibrated Accuracy*. Thanks to reliance on real-world development data, the methodology offers a validated level of precision sufficient for the early stages of design, where rough yet trustworthy estimates are more valuable than detailed simulations.

Calculation Logic and Workflow

1. *Not Suitable for Final Design Verification*. The tool does not replace detailed 3D modeling, CFD, or FEA simulations. It is not intended for final validation of thermal or structural loads or for generating detailed manufacturing documentation.

2. *Limited to Typical SRM Architectures*. The methodology assumes common motor structures, such as bonded charges, single-chamber configurations, and standard nozzle geometries. Unconventional or experimental designs may fall outside its scope of validity (Ellis & Keller, 1975).

3. *Empirical Dependency on Historical Data*. Accuracy is heavily dependent on statistical data from past development projects. If new materials or production technologies are introduced (e.g., additive manufacturing, novel composites), recalibration may be required.

4. *Simplified Modeling of Transient Phenomena*. The current implementation does not account for certain time-dependent effects such as dynamic pressure spikes, ignition transients, or complex grain burnback patterns, which can be relevant in some mission scenarios.

Despite these limitations, the methodology fills a critical gap in the engineering workflow by offering a practical and validated tool for the early evaluation of SRM concepts – bridging the divide between idea and high-fidelity simulation (Zosimovych, 2021).

Future Directions

The development of the automated evaluation methodology represents an important step toward accelerating the preliminary design of SRMs. However, continued advances in propulsion technologies, materials, and computational tools offer numerous opportunities for expanding and refining the system's capabilities. This section outlines potential future enhancements and research directions (Li et al., 2025).

Integration with Modern Design Environments

To improve usability and facilitate design iteration, the methodology can be integrated with: computer-aided design systems for geometry synchronization; multiphysics solvers for thermal, structural, and fluid interaction simulations; model-based systems engineering platforms for broader system-level optimization. Such integration would allow the tool to transition from a standalone calculator into a component of a complete digital design workflow (Rohini et al., 2022).

Support for Advanced Materials and Manufacturing

Emerging technologies such as additive manufacturing, carbon composite casings, and new high-energy propellants require updated modeling approaches. Future versions of the methodology could: include new material property databases; account for hybrid grain geometries; model manufacturing constraints and tolerances. This would enable accurate evaluations of cutting-edge SRM designs that go beyond legacy configurations.

Multi-Objective Optimization and AI Integration

Introducing multi-objective optimization algorithms would allow designers to balance trade-offs between mass, cost, performance, and reliability more effectively (Miller, 1971). Additionally, incorporating machine learning techniques could assist in: predicting optimal parameter combinations based on historical outcomes; reducing computation time for high-dimensional design spaces; identifying non-obvious patterns or failure risks Emerging.

Extension to Multi-Stage Propulsion Systems

While the current methodology is tailored for single-stage SRMs, it could be extended to evaluate multi-stage propulsion stacks by modeling stage separation dynamics; optimizing interstage mass distribution; evaluating stage-specific constraints and sequencing. Such an upgrade would support full mission analysis and increase the relevance of the tool for complete missile and launch vehicle systems (Kamm & Gany, 2008).

Experimental Data Enrichment

To improve accuracy and broaden applicability, future work may focus on: expanding the empirical database with new test results; refining calibration models for specific propellant types and nozzle technologies; validating results across international SRM design programs for generalization. These directions offer a roadmap for transforming the current methodology into a comprehensive and intelligent design assistant, capable of supporting next-generation propulsion development under both traditional and advanced manufacturing paradigms (Terzic et al., 2011).

Conclusion

This paper raises the issue of developing a structured methodology for the automated evaluation of SRMs during the preliminary design phase. Developed on the basis of analytical models and statistical calibration using real-world data from Yuzhnoye State Design Office, the methodology enables engineers to quickly and reliably estimate key motor parameters without the need for detailed simulations or cross-disciplinary coordination.

The system supports a wide range of input parameters and performance criteria, making it applicable to various classes of missile systems – from tactical to intercontinental (Mishra et al., 2022). It provides a fast and efficient tool for evaluating thrust performance, internal ballistics, thermal conditions, and structural characteristics within a unified framework. Through algorithmic implementation and optimization logic, it facilitates the comparison of hundreds of design options in a matter of minutes, significantly accelerating early-stage decision-making.

Validation against previously developed motors demonstrates that the methodology delivers accurate predictions within acceptable engineering tolerances. Although not intended for final verification or certification, it serves as a powerful screening and optimization tool, helping to identify promising design directions early in the development cycle (Zhang et al., 2025).

By bridging the gap between conceptual ideas and detailed simulation environments, this methodology fills a critical niche in the missile design workflow. With future enhancements – such as support for advanced materials, integration with CAD systems, and AI-driven optimization – it has the potential to evolve into a comprehensive design assistant for modern propulsion development.

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