ЗВІТ ЗА 2-Й РІК АСПІРАНТУРИ (2025–2026)

Структурно-параметричний синтез компоновок (конструкцій) наземних безпілотних логістичних систем

Аспірант: **Максим ДОЩЕНКО** (Спеціальність G9)

Науковий керівник: проф., д. т. н., **Віталій ПАСІЧНИК**

Виконання навчальної та наукової складової

Освітня складова

План виконано в повному обсязі

7 дисциплін

Оцінки: 90–98 балів

Вивчені дисципліни:

- Педагогічна практика
- Надтверді матеріали інструментального призначення
- Методи проектування і розрахунку машин і конструкцій
- Діагностика та системи забезпечення якості
- Механіка і оброблення композитів
- Функціональний підхід в машинобудуванні та матеріалообробці
- Надійність машин і конструкцій

Наукова складова: 1-й рік

- **Публікації:** Опубліковано 1 наукову статтю англійською мовою.
- **Конференції:** Здійснено 3 виступи на конференціях з публікацією тез.
- **Патенти:** Отримано 2 патенти на корисні моделі.

Наукова складова: 2-й рік (звітний)

- **Публікації та тези:** Подано до публікації 1 статтю англійською мовою, опубліковано тези на 1й конференції.
- **Заявка на винахід:** Подано 1 заявку (триває кваліфікаційна експертиза).
- **Заявка на корисну модель:** Подано 1 заявку (успішно пройшла експертизу, патент на етапі випуску).

Грантова діяльність та визнання:

- Подано заявку на європейський грант *Horizon* (розробка інноваційного дрона для пожежогасіння).
- Участь в конкурсі та *Brave 1* на виготовлення спеціалізованого пожежного дрону для потреб ДСНС України.

Стан підготовки дисертації: Розділ 1

Аналіз стану проблеми та огляд конструкцій наземних роботизованих комплексів (НРК)

Статус розробки

Висока степінь готовності

80%

Готовність матеріалів розділу

Опрацювання джерел:

Досліджено понад 80 релевантних джерел, з яких 45 - наукові англомовні статті 2015-2025.

Основні результати:

- Проведено огляд існуючих конструкцій НРК та їх класифікацію.
- Проаналізовано методології синтезу стосовно роботизованих платформ.
- Визначено критичні технології виготовлення НРК, виявлено вузькі місця в існуючих виробничих підходах.
- Сформовано підходи до проведення експериментального дослідження.

Висновок: Окреслено проблему дослідження — забезпечення технологічної масштабованості на етапі структурно-параметричного синтезу.

Публікація:

Матеріали з розділу 1 оформлено як англомовну статтю для фахового журналу ***«Ukrainian Journal of Mechanical Engineering and Materials Science»*** (опублікована у 2025 р.).

Стан підготовки дисертації: Розділ 2

Структурно-параметричний синтез НРК.

Статус розробки

Значне виконання

60%

Готовність матеріалів розділу

Ключова спрямованість:

Розробка класифікаційної моделі, математичного апарату синтезу та їх практична апробація.

Основні теоретичні здобутки:

- **Класифікаційна модель EPAM:** Запропоновано модель для систематизації рішень (оформлено у вигляді статті), де конструкція визначається як множина: **TR = E × P × A × M**
  E – середовище, P – призначення, A – автономність, M – мобільність).
- **Методологія синтезу:** Розроблено багатокритеріальний математичний апарат, який звужує простір рішень від загальних вимог до множини раціональних конструкцій (через перевірку сумісності, розрахункову модель та Парето-відбір). **(у жовтні 2026 - подання статті - Scopus).**

Наповнення розділу (в процесі):

- **Конструктивне забезпечення:** Формування підрозділу з розрахунками параметричних моделей.
- **Практична апробація:** Наповнення підрозділу 2.4 застосуванням методу синтезу до модульної логістичної платформи UMP

ФРАГМЕНТИ ПУБЛІКАЦІЇ
1
(опубліковано)

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UNMANNED GROUND-BASED ROBOTIC SYSTEMS: CLASSIFICATION AND ANALYSIS

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Abstract. The integration of unmanned ground-based robotic systems into logistics and other automation-intensive sectors has notably expanded in recent years. Despite their increasing prevalence, the lack of a unified classification framework has complicated the systematic selection and deployment of these platforms. This research has been initiated to address this gap by developing the EPAM classification system, which incorporates Environment, Purpose, Autonomy, and Mobility as core multidimensional criteria.

The purpose of this study is to develop a coherent and technically grounded taxonomy for Unmanned Ground Vehicles (UGVs), with a particular focus on logistics and multifunctional applications. The methodology has involved a comprehensive literature review, systematization of existing classification approaches, and a comparative analysis of their scope and limitations. The EPAM framework has been defined in terms of discrete sets of application environments (e.g., paved roads, dirt roads, rough terrains), intended functions (e.g., transport, patrol, combat, supply), autonomy levels (from remote-controlled to fully autonomous), and platform mobility types (wheeled, tracked, legged, hybrid).

Key findings have demonstrated that current classification systems fail to standardize vital technical parameters such as drive configuration, modularity, and autonomy architecture. Therefore, A consistent taxonomy has been proposed, enhancing technical communication between developers and users and supporting more informed decision-making. The novelty of the approach lies in its formalized, multidimensional structure, which enables the coverage of real-world UGV application scenarios and environmental constraints, including transitional terrains, wet surfaces, and complex, obstacle-ridden areas.

A preliminary classification of existing UGV platforms has been initiated to verify and validate the applicability of the EPAM model. This step will serve as empirical support for the robustness and scalability of the proposed system. The practical value of the study is reflected in its potential to foster interoperability standards, enhance procurement specifications, and expedite the development of adaptive UGV platforms for dynamic logistics operations.

Future investigations are expected to focus on refining classification criteria based on operational feedback, integrating Artificial Intelligence (AI)–based perception technologies, and applying the EPAM system in simulation and field-testing environments. The proposed framework offers a foundation for further scientific exploration in ground robotics and operational planning under uncertainty.

UGV – movement along a fixed, predefined path using encoded trajectories. Obstacle detection may be available, but autonomous response is limited (e.g., factory AGV systems); **Level 4**: Automated-UGV – capable of deviating from pre-planned routes to avoid obstacles. Environmental processing algorithms allow trajectory adjustment (e.g., Autonomous Mobile Robots used in warehouse operations); **Levels 5–8**: Autonomous-UGV systems with full autonomy in navigation, decision-making, and adaptation. These include advanced sensor integration, AI modules, and embedded decision logic. Typical applications include military operations, logistics, search and rescue, and exploration in off-road environments.

Additional autonomy factors include not only driving control but also: *Navigation* – ability to plan and reroute dynamically; *Decision-making* – capacity to process sensory inputs and make tactical choices; *Organizational interaction* – coordination with other vehicles under centralized or decentralized control; *Environmental complexity* – the capacity to function in structured and unstructured environments.

The ASTM F45 autonomy classification extends the SAE J3016 model by enabling finer granularity across industrial, logistics, and military unmanned platforms. The operational context–mission complexity, environmental dynamics, and operator interaction–substantially affects the level of autonomy required. Continued advancement of autonomous systems necessitates improvements in testing protocols and standardization frameworks [15].

An essential aspect of UGV classification is defining interaction with other unmanned systems, particularly aerial vehicles, which are frequently used in combined operational scenarios. Dinelli et al. [17] review hybrid drone-UGV configurations, highlighting the relevance of a comprehensive classification approach that incorporates multi-agent integration. Factors such as interaction, coordination, and collaborative mission planning between ground and aerial unmanned platforms are crucial for enhancing UGV functionality and ensuring operational effectiveness in complex mission environments.

Adapting the above-mentioned classification approaches for UGVs, a structured classification based on the autonomy criterion is introduced:

The set defined by Autonomy *{A} = { p (programmable)* – programmable systems; *rc (remote controlled)* – remotely controlled systems; *a (autonomous)* – autonomous systems; *o (other)* – other types of control*}*.

Accordingly, the notation includes: A_p – programmable platforms capable of executing various tasks based on predefined algorithms or programmed routines; A_{rc} – remotely controlled platforms operated by a human; A_a – platforms capable of performing tasks independently, including navigation and decision-making based on sensor inputs, AI, and adaptive mechanisms for complex operations in diverse environments; A_o – platforms operated through other control methods, such as bio-interface control systems.

Platforms with hybrid autonomy types are denoted as subsets of *{A}*. For instance, $A_{\{rc,\ a\}}$ indicates platforms that support both remote and autonomous control modes.

The Mobility criterion is defined by the set *{M} = { w (wheel)* – wheeled platforms; *t (track)* – tracked platforms; *l (leg)* – legged platforms; *o (other)* – platforms with alternative mobility systems *}*.

The set *{M}* may include the following values: M_w – platforms with wheeled propulsion; M_t – tracked platforms; M_l – legged platforms; M_o – platforms with alternative movement mechanisms, such as screw drives. Platforms with combined propulsion types are denoted as a subset of *{M}*. For example, $M_{w,t}$ indicates a wheel-track hybrid platform; $M_{\{w,l\}}$ refers to platforms capable of movement using both wheels and legs.

Subtypes of wheeled platforms include: M_{w1} – single-wheeled platforms that maintain balance using gyroscopic sensors (e.g., Segway-type); M_{w2} – two-wheeled balancing robots (similar to hoverboards); M_{w3} – three-wheeled systems offering increased stability and manoeuverability; M_{w4} – classic four-wheeled UGVs; M_{wm} – multi-wheeled platforms (6+ wheels) used for enhanced off-road capability. Lopatka et al. [18] investigated the terrain mobility of hydrostatically driven UGVs.

Subtypes of tracked platforms: M_{tr} – traditional rigid-frame tracked platforms with even weight distribution; M_{th} – hybrid wheel-track systems designed for adaptive movement; M_{tf} – flexible tracked

Keywords: unmanned ground vehicle (UGV), mechanical engineering, machine design, multi-dimensional classification, robotic systems, logistics automation, autonomous transport platform, mobile robotics operational context.

Introduction

Modern *unmanned ground robotic systems* (UGRSs) technologies have been increasingly integrated into a wide range of domains that require process automation, operational efficiency, and enhanced safety. Of particular significance is their application in the field of logistics, where these systems have been utilized to perform autonomous transportation of cargo, including evacuation tasks and the delivery of critical resources and materials to inaccessible or hazardous locations. Due to these capabilities, UGRSs are well-positioned to play a crucial role in enabling flexible and rapid response solutions within contemporary logistical operations.

According to the analytical agency *Fortune Business Insights*, the global *unmanned ground vehicle* (UGV) market was valued at USD 3.07 billion in 2023, with projected growth to USD 6.35 billion by 2032, corresponding to a compound annual growth rate (CAGR) of 8.6 % [1]. In contrast, *Precedence Research* forecasts even faster growth, estimating the market to reach USD 3.60 billion by 2024 and USD 8.80 billion by 2034, with a CAGR of 9.35 % [2]. These estimates indicate a stable and increasing demand for UGVs in the near future. Regarding market structure, small-scale UGVs accounted for 58 % of the market in 2024, demonstrating a preference for compact solutions designed for specific tasks. Moreover, 65 % of the market share was held by tracked platforms, which offer high mobility in challenging environments, and 81 % of the systems were operated remotely.

Problem Statement

The significance of UGRSs in military and logistic applications has increased under modern hybrid conflicts, which has stimulated research for their regulation, development, and application, as indicated by Zinko et al. [3]. The development of UGRSs has legislated a set of key strategic directions for achieving asymmetric superiority over an adversary. The outlined key vectors for forecasting the development of unmanned systems, the presented vision of the UGRS ecosystem, the conducted SWOT analysis, and the scenario-based forecasting methodology involving a modified branch method as part of a broader foresight analysis [4] confirm the urgent need for unified approaches to the systematization of such systems, particularly in the form of classification models that consider environmental conditions of application, functional purpose, levels of autonomy, and mobility. The development of such a model represents the objective of the present study.

Therefore, the creation of a unified, multidimensional classification framework for UGRSs – based on drive type, structural configuration, and autonomy level would constitute a significant step toward standardization, thereby improving the efficiency of collaboration among all stakeholders involved in the development and implementation of robotic platforms.

Review of Modern Information on the Subject of the Paper

Available sources do not offer a generalized or standardized classification of UGRSs based on key technical parameters such as drive type, structural layout, or level of autonomy. Nonetheless, several isolated classification approaches have been proposed, focusing on intended use (e.g., combat, reconnaissance, transport), type of operational environment (e.g., ground, aerial, maritime), and levels of autonomy, which range from remote control to complete autonomy with decision-making capabilities.

Drive type (e.g., electric, hybrid, diesel) is usually mentioned in the context of energy efficiency analysis but is not incorporated as a component of a systemic classification framework. Similarly, structural layout (e.g., wheeled, tracked, modular) is occasionally used as a selection criterion for specific applications, although no universally accepted formalized approach currently exists. The lack of consistent terminology and a standardized classification methodology often complicates the formulation of technical specifications, leading to misinterpretation of system requirements.

platforms capable of shape adaptation for improved terrain navigation. Odedra et al. [19] explored mobility improvements in tracked UGV platforms.

Subtypes of legged platforms: M_{lt} – bipedal humanoid robots for uneven terrain; M_{ld} – quadrupeds offering high stability (e.g., Spot by Boston Dynamics); M_{lk} – hexapods used in research and rescue missions; M_{lm} – multi-pedal robots adaptable to diverse surfaces. Durst et al. [20] provided an overview of mobility modelling for autonomous UGV.

Subtypes of platforms using non-typical mobility methods (M_o): M_{os} – snake-like robots employing wave motion for narrow spaces; M_{oj} – jumping robots using impulse propulsion; M_{ov} – screw-propelled platforms effective in sand or snow; M_{om} – magnetic robots capable of moving along vertical or metallic surfaces; M_{oh} – hybrid systems combining multiple mobility mechanisms (e.g., leg-track hybrids). According to Odedra et al. [21], mobility issues of hybrid systems.

The complete set of technical solutions for ground robotic systems is represented as a Cartesian product of the defined sets:

$$TR = E \times P \times A \times M, \quad (1)$$

where TR denotes a technical solution, and E, P, A, and M are the sets defined according to the rules outlined above.

Examples of the identification of two domestic and two foreign ground robotic platforms are presented in accordance with the proposed classification framework.

Classification samples

UGV	Classification description
BRO-U6, Tracked UGV	$E_{\{pr,dr,rt\}}P_{\{p,a,o\}}A_{\{p,rc,a\}}M_{\{t,l\}}$
TerMIT – Tracked Modular Infantry Transporter	$E_{\{dr,rt,o\}}P_{\{p,rc,o\}}A_{\{p,rc\}}M_{\{t,l\}}$
THeMIS UGV, Milrem Robotics	$E_{\{dr,rt,o\}}P_{\{p,rc,o\}}A_{\{p,a,o\}}M_{\{t,l\}}$
Rheinmetall Mission Master SP	$E_{\{dr,rt,o\}}P_{\{p,rc,o\}}A_{\{p,rc,a\}}M_{\{w,t\}}$

It is evident that comparing platforms is relatively simple when they are equivalent, and it becomes more complex as the divergence between their descriptions increases. Comparing models with identical descriptions should be carried out based on technical specifications, which are beyond the scope of the proposed classification system.

For comparison purposes, we recommend using a conformity matrix, an example of which is provided in Figure, illustrating the comparison of two domestic ground robotic systems: BRO-U6 and TerMIT. The matrix should be constructed in two stages. In the first stage, a qualitative analysis of both systems is conducted to identify common groups of characteristics for comparison and to highlight potential advantages. In the matrix, cells corresponding to features absent in a particular system are "blocked" (crossed-out cells). If the other system possesses the parameter, the corresponding cell is marked as a potential competitive advantage (we propose **shading it in gray**).

E		P		A		M	
E_{pr}		P_p		A_p		M_w	
E_{dr}		P_{rc}		A_{rc}		M_t	
E_{rt}		P_a		A_a		M_l	
E_o		P_o		A_o		M_o	
BRO-U6	TerMIT	BRO-U6	TerMIT	BRO-U6	TerMIT	BRO-U6	TerMIT

EPAM conformity matrix

1. **Soft and loose surfaces**: *Sand*: loose soil that complicates traction, particularly for wheeled platforms, while tracked and legged systems exhibit superior mobility (desert missions, reconnaissance) [8]; *Snow covers*: As reviewed by Researcher [9], robotic systems optimized for rugged terrain, snowy or icy terrain that limits traction and requires specific technologies, such as studded tracks (arctic and high-altitude operations).

2. **Wet or unstable surfaces**: *Swamps and bogs*: water-saturated terrain with low load-bearing capacity; tracked and legged platforms are better adapted (rescue and agricultural operations) [8]; *Puddles and colloidal soil mixtures* are shallow water surfaces that pose immersion risks (construction sites, military applications). Ersü et al. [10] systematically reviewed radar technologies applicable to UGVs.

3. **Transitional surfaces**: *Complex terrain*: Maaiveld et al. [11] studied tactical terrain analysis methods. Combinations of solid, soft, sandy, and wet areas create mixed conditions that require adaptive control systems (combat zones, rescue missions).

4. **Obstacles and barriers**: *Rugged terrain*: rocks, ravines, and tree-filled areas requiring enhanced chassis adaptability (forest reconnaissance, mountain operations) [9]; *Water obstacles*: shallow streams and water bodies that can be crossed using special tracks or waterproof electronic systems (military missions, engineering tasks) [8].

The set defined by the Environment criterion *{E} = {pr (paved road)* – for deployment on paved roads with markings; *dr (dirt road)* – for deployment on unpaved or dirt roads; *rt (rough terrain)* – for deployment in off-road conditions; *o (other)* – for deployment in all different conditions*}*.

Accordingly, platforms may be denoted using the following values: E_{pr} – designed for operation on paved roads, E_{dr} – on dirt roads, E_{rt} – in rough terrain, and E_o – in other environments. Platforms with multi-environment deployment capability may be designated as a subset of *{E}*. For example, $E_{\{pr,dr\}}$ indicates platforms operable on both paved and dirt roads, while $E_{\{pr,\ rt,o\}}$ refers to those suitable for any environment except paved roads.

Classification according to **Purpose**:

t (transportation): transport of cargo, resource delivery, and casualty evacuation. An example is the use of UGVs for delivering ammunition, supplies, or medical equipment.

p (patrol and reconnaissance): intelligence collection, terrain monitoring, object surveillance, and perimeter patrol. An example is UGVs equipped with cameras and sensors for real-time data collection and situational awareness, as detailed on Wikipedia [12];

c (combat): execution of combat tasks such as fire support and participation in offensive or defensive operations. Example: Mappes et al. [13] documented instances of fully robotic military operations – 'Ukrainian defense forces conducted the first fully robotic attack;

e (explosive ordnance disposal): detection, neutralization, and removal of explosive hazards, including mines and unexploded ordnance. According to Krivtsun and Kuprienko [14], UGVs can be effectively used for the safe disposal of explosive devices;

s (supply): carriage and use of support modules or systems to assist other operational tasks. Example: UGVs equipped with generators, communication gear, or other logistic payloads;

o (other): specialized applications such as training, demonstration, or experimental tasks. Example: UGVs used in academic programs or prototype testing.

The Purpose criterion is represented by the set *{P} = {t (transportation)* – for cargo transport, resource delivery, and casualty evacuation; *p (patrol)* – for patrol missions and surveillance operations; *s (supply)* – for logistic support (carrying various payload modules); *o (other)* – for all different applications*}*.

At the second stage, the content of the unhighlighted cells is filled with technical specifications that can be compared on a unified basis (not shown in the figure), enabling a quantitative comparison.

Based on this analysis, engineers can conclude the advantages and disadvantages of the selected pair of ground robotic systems.

Conclusions

The issue of establishing a basis for comparing various ground robotic systems should be further specified within the "Mobile Robots" class. The proposed classification system "EPAM" is based on four key attributes: E – environment of operation, P – purpose, A – autonomy level, and M – mobility type.

A set of possible values has been defined for each attribute, and it has been demonstrated that the description of a specific technical solution constitutes a four-dimensional Cartesian product of these sets. The proposed system's applicability has been illustrated through examples involving both domestic and foreign robotic platforms.

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Стан підготовки дисертації: Розділ 3

Технологічне забезпечення виготовлення НРК

Статус розробки

Значне виконання

60%

Готовність матеріалів розділу

Ключова спрямованість:

Перехід до ЧПК-центрованих стратегій виробництва та оцінка технологічної масштабованості.

Основні здобутки:

- **Критерії оцінювання:** Сформульовано критерії оцінювання технологій з точки зору їх здатності до масштабування (ресурсна напруженість, технологічна вартість, аутсорсингова гнучкість).
- **Оцінка базових технологій:** Проведено оцінку базових технологій (лазерне різання, CNC-пробивання, самобазуючі з'єднання), обґрунтовано перехід до ЧПК-центрованих стратегій виробництва.
- **Технологічно-масова еластичність:** Введено поняття «технологічно-масової еластичності», яке дозволяє обґрунтувати зміну маси заради скорочення часу та спрощення виготовлення.

Публікація:

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ФРАГМЕНТИ ПУБЛІКАЦІЙ
(подано до редакції - вересень 2026)

Assessment of the Technological Suitability of Unmanned Ground Vehicles for Rapid Production Scaling

Abstract

The aim of this article is to develop a mathematical and logical approach to assessing the technological suitability of unmanned ground vehicles (UGVs) for the rapid scaling of their production. It is shown that, under conditions of a shortage of skilled manual labour, limited time for production preparation, and the need to engage a distributed network of contractors, the functional performance of a prototype does not guarantee that production can be scaled rapidly to the required volumes. Technological scalability is proposed as an integral property of both the UGV design and its manufacturing route. The methodology combines criteria for total resource intensity, full technological cost per operation, technological–mass elasticity, and outsourcing flexibility. A multicriteria problem statement and an algorithm for selecting a design-and-manufacturing strategy are developed, with verification of functional, mass, repairability, and production constraints. The expediency of CNC-centred strategies, self-locating interfaces, universal tooling, flexible sheet-cutting technologies, and automated preparation of spatial frame elements is substantiated. The scientific novelty lies in formalising the trade-off among mass, machine time, manual labour, and the suitability of a design for distributed manufacturing. The practical significance of the approach is that scalability can be considered at the early stages of UGV design and solutions can be selected that shorten the production launch cycle without violating mandatory operational requirements. The results can be used when designing a UGV prototype intended for serial production.

Keywords: unmanned ground vehicle; technological scalability; design for manufacturing and assembly; production ramp-up; CNC; self-location; multicriteria selection.

Introduction

Relevance of the problem of UGV technological scalability

The development of unmanned ground vehicles (UGVs) in Ukraine is part of an asymmetric response to Russian aggression. Their use reduces risks to personnel and improves the effectiveness of logistics, evacuation, reconnaissance, and engineering missions.

Drone proliferation is regarded as a systemic trend in modern warfare [1], while the development of unmanned systems is treated as a priority of military-technical policy [2]. The conceptual and life-cycle framework of this field is established by the principles for the development of robotic systems in the Armed Forces of Ukraine [3].

Current UGV development is based on initiative-driven solution search, rapid testing, and adaptation to tactical requirements, threats, the available component base, and manufacturing capabilities. As a result, heterogeneous platforms are being developed simultaneously, differing in layout, propulsion, payload capacity, control, autonomy, and integration capabilities.

Studies of combat UGVs systematise their logistics, engineering, reconnaissance, and evacuation functions [4]. Ukrainian experience in 2022–2025 also confirms the need for the rapid adaptation of platforms to changing operating conditions [5, 6].

Competition among layouts and configurations accelerates the search for effective solutions; however, functionally evident design concepts are quickly reproduced by other manufacturers. Long-term advantage therefore increasingly depends on the suitability of a design for manufacture, modification, repair, and scaling.

In this study, technological scalability S is treated as an integral characteristic dependent on several groups of parameters:

$$S = f(S_t, S_a, S_o, \dots)$$

where S_t is design-manufacturability; S_a is assembly suitability and S_o organisational suitability for distributed or outsourced production; and S_r is repairability and suitability for upgrading.

Each of these components, in turn, can be represented through a set of comparable dimensionless expertly normalised parameters. The following indicators are particularly important for rapid UGV scaling:

$$T_{lead},\quad T_{man},\quad T_{mach},\quad C_{setup},\quad C_{post},\quad D_{tool},\quad P_{flex},\quad Q_{max}$$

The weights assigned to the indicators depend on production conditions: machine time is important for a stable series, whereas manual labour, assembly, and unique tooling become critical during rapid ramp-up, labour shortages, and frequent changes.

The methodological basis for this set of parameters is Design for Manufacturing and Assembly (DFMA). The systematic review by Formentini, Boix Rodríguez, and Favi demonstrates the capabilities and limitations of DFMA for complex mechanical products [22], while the CAD-integrated approach of Campi et al. enables manufacturing and assembly problems to be identified during 3D modelling [23]. The works of Favi and Germani; Mathieson, Wallace, and Summers; and Favi, Garziera, and Campi further specify, respectively, the influence of architecture and interfaces on assemblability, [24], the relationship between assembly time, part count, and the complexity of physical connections [25], and the early identification of manufacturing problems in welded structures [26].

The methodology then forms a user system of correlated criteria:

$$K_{tech} = \frac{C_{op} + C_{setup} + C_{post} + C_{ctrl}}{Q}$$

The criteria [illegible] characterise resource intensity, full technological cost, the trade-off between mass and cycle time, and suitability for outsourced production.

The criteria C_{res}, K_{tech}, ε_{tm}, and P_{flex} are subsequently considered as interconnected elements of a unified methodology for assessing a design's technological suitability for scaling.

Total resource intensity criterion for the production process

The criterion must account not only for operation duration but also for resource scarcity: an hour on commonly available CNC equipment and an hour of work by a skilled welder or assembler may have different levels of criticality.

To formalise this difference, the following total resource intensity criterion is proposed:

$$C_{res} = \alpha T_{man} + \beta T_{mach} + \gamma T_{setup} + \lambda T_{ctrl}$$

where C_{res} is the conditional total resource intensity; T_{man} and T_{mach} are manual labour and machine time; T_{setup} is process-preparation, changeover, and tooling time; T_{ctrl} is inspection, alignment, and correction time; and $\alpha, \beta, \gamma, \lambda$ represent the scarcity or criticality of these resources.

For a preliminary comparison of alternatives, the criterion may be presented in simplified form:

$$C_{res} = \alpha T_{man} + \beta T_{mach} \to \min$$

However, in an extended version of the model, T_{setup} and T_{ctrl} should be included explicitly because they often determine whether a design is unsuitable for rapid scaling. A design may require relatively little effort to manufacture individual parts but still demand complex alignment, actual repeated geometric inspection, and numerous [illegible] operations. Such a design's actual scalability would then be low.

The coefficients $\alpha, \beta, \gamma, \lambda$ are not constant across all production conditions. They must reflect the actual availability of the relevant resources. When skilled manual labour is scarce and CNC services are relatively more accessible, the following relationship may apply:

$$\alpha \gg \beta$$

Thus, more complex CNC processing may be rational if it substantially shortens manual assembly.

This leads to an important technological conclusion: for UGVs that must be scaled rapidly, minimising machine time is not always appropriate as an independent objective. On the contrary, increasing T_{mach} may be justified if it produces a substantial reduction in T_{man}, T_{setup}, and T_{ctrl}. This is the basic mathematical justification for adopting CNC-centred manufacturing strategies, self-locating joints, automated cutting of tubular elements, and universal tooling.

Full technological cost criterion for an operation

Full technological cost is used to compare alternative manufacturing processes.

The multicriteria nature of this choice is confirmed by Lukić et al., who consider cycle time, flexibility, material utilisation, quality, and operating cost among the process criteria [27]. Eddy et al. emphasise that late process selection results in losses of time, cost, or functionality [28]. Integrated product–process design must relate material, equipment, requirements, and a multicriteria decision [29], while automated manufacturability feedback can be implemented at the conceptual stage [30].

In general form, the full technological cost criterion can be expressed as:

$$K_{tech} = \frac{C_{op} + C_{setup} + C_{post} + C_{ctrl}}{Q}$$

where K_{tech} is the full technological cost of one acceptable part; C_{op} is direct operating cost; C_{setup} is the cost of preparation, changeover, programming, or tooling; C_{post} is post-processing cost; C_{ctrl} is the cost of inspection and correction; and Q is the number of acceptable parts in the batch.

When comparing laser cutting and CNC punching, C_{ctrl} must be considered alongside C_{op}, C_{setup}, and C_{post}, because for UGVs it is important not only to obtain the correct contour but also to ensure that the part is suitable for self-location, welding, or modular assembly.

This criterion avoids an oversimplified comparison of technologies based only on cutting speed or hourly machine rate. For example, laser cutting may have an advantage for small batches, complex contours, and frequent product-mix changes because of its low C_{setup}. CNC punching may be more efficient for parts containing many holes, repetitive geometry, or a need to form dimples, louvres, flanges, or other features that reduce subsequent manual finishing.

Thus, a process is assessed by its effect on the entire route: reduced finishing, simpler assembly, and simpler locating may justify a higher cost for an individual operation.

Technological–mass elasticity coefficient

The technological–mass elasticity coefficient evaluates whether an increase in mass is acceptable in exchange for a shorter production cycle and less manual labour.

In general form, the coefficient can be expressed as:

A more complex CNC contour or a slight increase in mass is acceptable if self-location eliminates special tooling and additional operations assembly. [illegible]

Selection of blanking technology for UGV sheet-metal parts

For UGV sheet-metal elements, the choice of cutting and forming processes determines cycle duration, assembly accuracy, finishing requirements, and scalability.

Laser cutting and CNC punching are complementary technologies; the choice depends on batch stability, contours, formed features, edge quality, and downstream operations.

The full technological cost criterion allows these technologies to be compared not by an isolated parameter but by their total impact on the manufacturing route:

$$K_{tech} = \frac{C_{op} + C_{setup} + C_{post} + C_{ctrl}}{Q}$$

A characteristic advantage of laser cutting is the low changeover cost C_{setup} when the design or part mix changes. In many cases, switching to a new part variant requires only preparation or modification of the control program, making laser cutting suitable for small and medium batches, highly variable designs, and rapid design iterations. This is particularly important for UGVs whose designs may change quickly in response to operational feedback.

The assessment of laser cutting accounts for power, speed, gas, and thickness [36], as well as the trade-off among productivity, kerf width, thermal effects, roughness, and surface quality [37, 38].

Laser cutting also has limitations that become critical during scaling. A large number of internal contours and perforations increases operation time because each feature requires a separate piercing cycle. For thin-sheet parts, additional factors may include thermal effects, warping, [illegible] formation, or the need to clean edges. In such cases, C_{post} and C_{ctrl} increase, that is, [illegible] ensuring that the part is suitable for assembly.

CNC punching, by contrast, may be appropriate for repetitive patterns: arrays of holes and perforations, and elements requiring pressure forming. These include dimples, louvres, flanges, technological projections, local stiffening features, or seating features for subsequent assembly. In such cases, the advantage of CNC punching lies not only in the speed of producing holes but also in the ability to integrate some forming operations into the cutting process itself.

From the standpoint of scalability, this is of fundamental importance. If a blanking process eliminates separate manual or bench-work operations and reduces additional drilling, threading, bending, or fitting, its effect on C_{res} may be positive even when additional tooling or tool-magazine setup is required.

Process selection must be based on the complete route:

$$K_{tech}^{laser} < K_{tech}^{punch}$$

for highly variable designs, small batches, and complex contours without a substantial number of formed features;

$$K_{tech}^{punch} < K_{tech}^{laser}$$

for repetitive parts containing many holes, perforations, or formed features that reduce subsequent finishing.

The comparison of laser cutting and CNC punching in terms of changeover, internal contours, thermal effects, hole arrays, and forming illustrates the application of the K_{tech} criterion to the selection of a manufacturing strategy.

Economic comparison of sheet-metal processes must include not only the operating rate but also [illegible] processes, changeovers, and bending, as demonstrated in the model by Bargelis and Jasaitis [39]. Combined laser–punch systems additionally require coordinated CAPP/CAM, nesting, and toolpath planning [40]. In CNC punching, hole quality depends on clearance, geometry, and tool wear [41], while burrs may require additional grinding, increasing C_{post}, [illegible], and K_{tech} [42].

Manufacture of thick-sheet load-bearing elements

Thick-sheet load-bearing elements form a separate group of UGV parts: suspension components, brackets, levers, supports, heavily loaded parts, and elements exposed to impact, vibration, or cyclic loading. Manufacturing such parts directly from rolled stock by complete milling or other machining may be technologically inefficient because of the large volume of material removal, substantial machine time, intensive tool wear, and high operation cost.

The evidence on abrasive water jet (AWJ) cutting likewise indicates that the entire route must be assessed. Unlike thermal cutting processes, AWJ does not alter the material structure in the cutting zone, which may be important for critical load-bearing elements. Hlaváč et al. demonstrate the effect of kerf taper and the difference between top and bottom kerf widths in thick steels [43], while Brandstätter et al. show the importance of waviness, striations, and surface roughness [44]. Yuvaraj and Pradeep Kumar demonstrate multicriteria optimisation of AWJ parameters using TOPSIS [45], whereas Arnaţan and Arici show the potential of simultaneous cutting of stacked S235JR sheets to increase productivity [46].

Limitations of AWJ include striations, geometric deviations, and taper, which can be compensated for by five-axis systems.

From the perspective of the proposed methodology, this solution should be assessed not only by the cost of AWJ cutting itself but by its entire manufacturing route:

$$K_{tech}^{AWJ} = \frac{C_{op}^{AWJ} + C_{setup}^{AWJ} + C_{post}^{AWJ} + C_{ctrl}^{AWJ}}{Q}$$

If AWJ cutting reduces the volume of rough machining, shortens the machine time required on expensive machining centres, reduces machining allowance, or avoids thermal deformation, it may be justified even when the direct operation cost is relatively high. In other words, its efficiency is determined not only by the local C_{op}^{AWJ} but also by reductions in the following route components:

$$C_{post}^{mach} \downarrow,\quad T_{mach}^{finish} \downarrow,\quad C_{ctrl} \downarrow$$

This is particularly important for UGVs because load-bearing elements are often critical to the reliability of the entire platform. Errors in selecting a blank-production technology may lead either to excessive use of expensive machine time, unstable quality, or the need for additional manual finishing. Thick-sheet parts should therefore be evaluated separately from thin-sheet body elements, and the technology for producing them should be selected with regard to both operational loads and the full technological cost of the route.

Self-locating slot-and-tab assembly interfaces

During scaling, manual alignment, individual fitting, and dependence on a welder's experience become critical constraints in the assembly of spatial units.

From the perspective of the total resource intensity criterion, assembly operations primarily increase T_{man}, T_{setup}, T_{ctrl}, and D_{tool}. If a design requires a unique welding fixture for each

this can lead to unstable geometry, difficulties in subsequent assembly, and increased inspection costs.

A tube laser cutting system integrates these steps into a single digitally controlled process and forms a substantial portion of the geometry directly during CNC profile cutting.

In an illustrative production trial, the complete set of blanking operations for a batch of tubular parts required 3 hours of machine time on a tube laser cutting system, whereas the conventional route required approximately 48 hours of manual labour by two skilled workers over three shifts. This ratio is an illustrative case rather than a universal benchmark for all products.

Formally, the effect of this automation can be expressed through the change in the components of C_{res}:

$$C_{res}^{classic} = \alpha T_{man}^{classic} + \beta T_{mach}^{classic} + \gamma T_{setup}^{classic} + \lambda T_{ctrl}^{classic},$$
$$C_{res}^{CNC} = \alpha T_{man}^{CNC} + \beta T_{mach}^{CNC} + \gamma T_{setup}^{CNC} + \lambda T_{ctrl}^{CNC}.$$

If the following condition is satisfied:

$$C_{res}^{CNC} < C_{res}^{classic}$$

then the CNC-centred strategy is appropriate even if machine time or the direct cost of the operation increases.

In substantive terms, a tube laser cutting system does more than replace one operation with another. It changes the entire logic of manufacturing a frame element: accuracy is created at a digitally controlled stage, the number of manual transitions is reduced, geometric repeatability is improved, and the prerequisites for subsequent self-location during assembly are established. The technology should therefore be considered not merely as a blanking process but as an element of a systemic scaling strategy.

Universal tooling and distributed production

Another important way to increase UGV scalability is to avoid excessive dependence on unique assembly and welding tooling. Specialised fixtures may be effective for stable, high-volume production of an unchanged design; however, they become a constraint when requirements change rapidly and design iterations are frequent. Each modification requires an adjustment or a new fixture, increasing T_{setup}, production-preparation cost, and time to serial launch.

Universal 3D welding tables, modular stops, and quick-change clamps, combined with self-location, reduce dependence on special fixtures and facilitate production transfer.

From the perspective of outsourcing flexibility, this means increasing P_{flex} because more contractors can fulfil the order without lengthy additional process preparation:

$$P_{flex} = \frac{N_{cap}}{N_{all}}$$

If a design requires a unique fixture, specialised experience in manual alignment, or a high proportion of fitting, the number of potentially capable contractors N_{cap} decreases. If a design is based on standard materials, CNC-manufactured parts, self-locating interfaces, and universal tooling, N_{cap} increases and so does P_{flex}.

The ability to transfer a design to several manufacturers without a loss of quality improves resilience to disruptions, production-site overload, and personnel shortages.

Summary of design-and-manufacturing strategies

Scalability is created by a system of interconnected decisions whose effects must be evaluated in terms of the production cycle, resource intensity, and outsourcing suitability.

The effects of the principal strategies can be summarised as follows:

Design-and-manufacturing strategy	Primary effect	Criteria affected
Laser cutting of sheet-metal parts	Flexibility when the product mix changes; low changeover cost	K_{tech}, C_{setup}, P_{flex}
CNC punching	Efficiency for repetitive parts, holes, and formed features	K_{tech}, C_{post}, T_{man}
AWJ cutting of thick-sheet elements	Reduced allowances and rough-machining volume	K_{tech}, T_{mach}, C_{post}
Tube laser cutting systems	Replacement of manual blank preparation with a digitally controlled operation	C_{res}, T_{man}, T_{ctrl}
Slot-and-tab interfaces	Self-location and reduced manual alignment	ε_{tm}, C_{res}, D_{tool}, P_{flex}
Universal 3D welding tables	Reduced dependence on unique fixtures	D_{tool}, T_{setup}, P_{flex}

The common logic of these strategies is to transfer accuracy, locating, and repeatability from manual labour and unique tooling to digital processes, standardised interfaces, and universal equipment.

Generalised algorithm for selecting a design-and-manufacturing strategy for UGV scaling

Purpose of the algorithm

The criteria C_{res}, K_{tech}, ε_{tm}, and P_{flex} support formalised selection of a UGV design-and-manufacturing strategy at an early design stage, while unit structure, joints, interfaces, materials, locating methods, and routes can still be changed. The algorithm identifies an alternative that meets functional requirements and improves production scalability; it complements, rather than replaces, engineering design, strength calculations, process-time estimation, and economic analysis.

Algorithm input data

At the first stage, a set of input parameters is formed that describes both the UGV design and the conditions under which its production will be scaled. These parameters include:

$$X = \{F_{req}, Q, V, M_{max}, \delta, G, H, B, R_{req}, O_{net}\}$$

where F_{req} is the set of functional requirements; Q is planned output; V is design variability; M_{max} is maximum permissible mass; δ is the material-thickness range; G, H, and B characterise geometric complexity, hole and perforation density, and locating and assembly complexity; R_{req} represents repairability requirements; and O_{net} characterises the available production network.

The input data combine technical and organisational parameters because the suitability of the same design depends on equipment, staff qualifications, and the available contractor network.

Formation of the set of feasible design-and-manufacturing alternatives

At the second stage, a set of alternative solutions is formed for a given design or unit:

$$A = \{A_1, A_2, \dots, A_n\}$$

where each alternative A_k includes not only a geometric solution but also the corresponding manufacturing and assembly route.

For example, UGV frame alternatives may include: A_1, a conventional lightweight design with manual locating and a specialised fixture; A_2, a self-locating slot-and-tab design with a more complex contour but shorter assembly time; A_3, a standardised design using tube-laser-cut elements; and A_4, a design adapted to a distributed contractor network with minimal dependence on unique tooling.

For each alternative, not only expected mass and functional performance but also the following process parameters must be determined:

$$T_{man,k},\quad T_{mach,k},\quad T_{setup,k},\quad T_{ctrl,k},\quad K_{tech,k},\quad P_{flex,k}$$

This approach prevents a design decision from being considered in isolation from production. Each alternative is assessed as a pair:

$$A_k = \{D_k, P_k\}$$

where D_k is the design solution and P_k is the corresponding manufacturing route.

Verification of mandatory functional and operational constraints

Before scalability is assessed, alternatives that do not meet minimum functional requirements are excluded.

Each alternative must satisfy the following constraints:

$$F_k \geq F_{min},\quad M_k \leq M_{max},\quad R_k \geq R_{min},\quad Q_k \geq Q_{req}$$

where F_k, M_k, R_k, and Q_k are, respectively, functional performance, mass, repairability, and achievable output; the remaining symbols denote their limit values.

Manufacturability therefore cannot justify loss of operability, excessive mass, or critical deterioration of operational properties.

Calculation of technological scalability criteria

First, total resource intensity is determined:

$$C_{res,k} = \alpha T_{man,k} + \beta T_{mach,k} + \gamma T_{setup,k} + \lambda T_{ctrl,k}$$

This indicator accounts for the fact that different types of time have different levels of criticality. When skilled manual labour is scarce, α may be substantially greater than β; consequently, a solution that increases machine time but reduces manual assembly may have a lower C_{res}.

Second, full technological cost is determined:

$$K_{tech,k} = \frac{C_{op,k} + C_{setup,k} + C_{post,k} + C_{ctrl,k}}{Q_k}$$

This indicator compares alternative technologies and their combinations.

Third, the technological–mass elasticity coefficient is determined for alternatives involving a deliberate increase in mass or geometric complexity in order to shorten the production cycle:

$$\varepsilon_{tm,k} = \frac{(T_{base} - T_k)/T_{base}}{(M_k - M_{base})/M_{base}}$$

Fourth, outsourcing flexibility is assessed:

$$P_{flex,k} = \frac{N_{cap,k}}{N_{all}}$$

or, in extended form:

$$P_{flex,k} = P_{E,k} \cdot P_{M,k} \cdot P_{Q,k} \cdot P_{A,k}$$

This indicator is important when scaling requires external capacity.

Normalisation of criteria and integral evaluation of alternatives

Because the criteria have different physical meanings, they should be normalised. For criteria that are to be minimised, such as C_{res} or K_{tech}, the following normalisation can be used. Its application and subsequent integral evaluation correspond to multicriteria manufacturing-process selection practice: Ghaleb et al. compare AHP, TOPSIS, and VIKOR using productivity, precision, complexity, flexibility, material utilisation, quality, and cost criteria [54]. This supports the proposed logic of S_k but does not eliminate the need to adapt the weights to a specific production situation.

$$\hat{C}_{res,k} = \frac{C_{res,k} - C_{res}^{min}}{C_{res}^{max} - C_{res}^{min}},$$

$$\hat{K}_{tech,k} = \frac{K_{tech,k} - K_{tech}^{min}}{K_{tech}^{max} - K_{tech}^{min}}.$$

For criteria that are to be maximised, such as P_{flex} or ε_{tm}, normalisation may take the following form:

$$\hat{P}_{flex,k} = \frac{P_{flex,k} - P_{flex}^{min}}{P_{flex}^{max} - P_{flex}^{min}}$$

After normalisation, the integral technological scalability score of an alternative can be expressed as:

$$S_k = w_P \hat{P}_{flex,k} + w_\varepsilon \hat{\varepsilon}_{tm,k} - w_R \hat{C}_{res,k} - w_K \hat{K}_{tech,k} - w_D \hat{D}_{tool,k}$$

where S_k is the integral score; $\hat{P}_{flex,k}$, $\hat{\varepsilon}_{tm,k}$, $\hat{C}_{res,k}$, $\hat{K}_{tech,k}$, and $\hat{D}_{tool,k}$ are the normalised criteria; and $w_P, w_\varepsilon, w_R, w_K, w_D$ are their weighting coefficients.

This expression should not be treated as a universal formula applicable to all UGVs without adaptation. Its purpose is to establish a transparent logic for comparing alternatives. In a specific project, weighting coefficients must be determined according to the production situation. If the main constraint is a shortage of skilled welders, the weight w_R associated with C_{res} increases. If distributed manufacturing is the primary objective, w_P increases. If rapid fixturelessness assembly is the key issue, ε_{tm} and the indicator D_{tool} receive greater weight.

Decision-making logic

At the final stage, the design-and-manufacturing strategy is selected using three rules.

Rule 1 — functional feasibility.

An alternative can be considered only if it satisfies the minimum functional, mass, repairability, and operational constraints:

$$F_k \geq F_{min},\quad M_k \leq M_{max},\quad R_k \geq R_{min}$$

Rule 2 — non-dominance.

An alternative is excluded if another alternative simultaneously has lower C_{res}, K_{tech}, and D_{tool} and higher P_{flex} and ε_{tm} without any reduction in functional performance.

Rule 3 — maximisation of integral scalability.

Among non-dominated alternatives, the one with the highest value of S_k is selected:

$$A^* = \arg\max_{A_k \in \mathcal{A}} S_k$$

Technological scalability is a systemic property of a UGV alongside functionality, adaptability, and repairability.

Conclusions

1. **UGV competitiveness has been formulated as an integral characteristic** combining functional performance, integration, adaptability, repairability, technological scalability, and life-cycle cost. This shifts assessment from an individual operational prototype to a design suitable for rapid and reproducible production.
2. **The limitations of a purely mass-centred approach have been substantiated.** Absolute mass minimisation may increase manual labour, assembly complexity, tooling dependence, and inspection time while reducing outsourcing flexibility; mass, functional, and production constraints must therefore be coordinated.
3. **A system of scalability criteria has been developed:** total resource intensity C_{res}, full technological cost K_{tech}, technological–mass elasticity ε_{tm}, and outsourcing flexibility P_{flex}. Together they formalise the effects of labour, machine time, changeover, post-processing, tooling, and contractor availability.
4. **Technologically adaptive, CNC-centred strategies have been substantiated.** Increased machine time or contour complexity is justified when it reduces manual assembly, fixture dependence, and inspection. The corresponding choices include laser cutting or CNC punching for thin sheet, AWJ for thick load-bearing elements, and self-locating interfaces, tube laser cutting, and universal 3D welding tables for spatial frames.
5. **A generalised selection algorithm and its limits have been defined.** The algorithm forms and filters alternatives, calculates and normalises criteria, checks dominance, and selects the highest feasible S_k. It complements rather than replaces strength, reliability, mobility, energy-consumption, and other engineering assessments and requires context-specific weighting coefficients.

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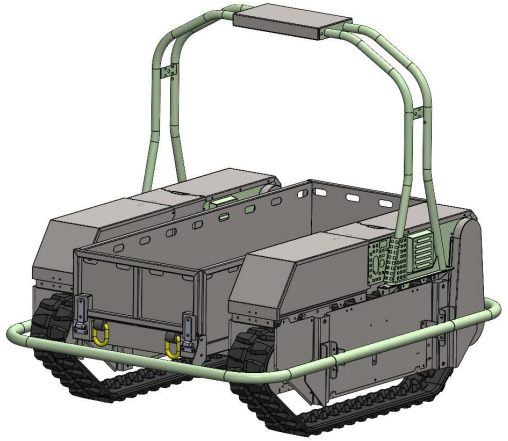
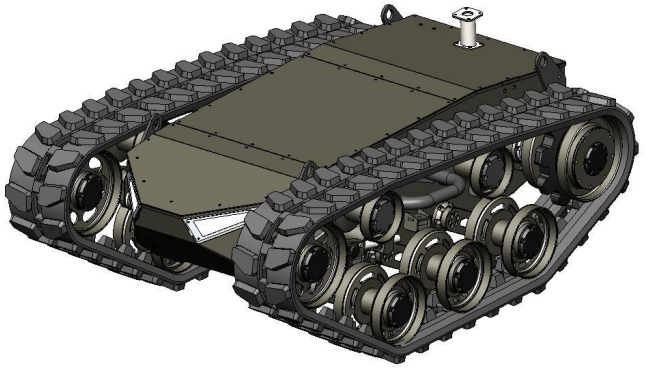
Стан підготовки дисертації: Розділ 4 та плани на 3-й рік

Експериментальні дослідження та підготовка НРК до маштабування виготовлення

Емпірична база - 2 моделі НРК “UMP”

Накопичено практичну базу даних на основі виготовлених та випробуваних 2-х моделей НРК власної конструкції (платформи BRO).

План дослідження на 3-й рік:

1. Детальне дослідження математичних параметрів технологічності виготовлення (з розділу 3) під час етапів підготовки НРК до виготовлення.
2. Проведення повноцінних експериментальних досліджень НРК (UMP “U6” та “L2.2”) для валідації математичного апарату оцінювання технологічної масштабованості.
3. Аналіз НРК як об'єктів інноваційної діяльності.
4. Апробація отриманих результатів, підготовка публікацій за результатами експериментів та остаточне оформлення тексту дисертації.