

A strategic–systemic–cybernetic model for managing elite rugby team preparation: a graph-based approach

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

DOI: <https://doi.org/10.58962/HSR.1354>

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How to cite: Kvasnytsya O, Tyshchenko V, Veritov O, Zaurenbek B, Zhunisbek D, Sokolova L, Skrypchenko I, Zholdosheva A, Asanalieva M, Ferenchuk B. A strategic–systemic–cybernetic model for managing elite rugby team preparation: a graph-based approach. *Health, Sport, Rehabilitation*. <https://doi.org/10.58962/HSR.1354>

Abstract

Background and purpose

Modern elite rugby is characterized by high variability of game situations, significant physical load, and stochastic competitive demands, which require effective and adaptive training management systems. At the same time, existing approaches are often fragmented and do not ensure integration of strategic, operational, and analytical components. The purpose of the study was to develop and theoretically substantiate a structural–functional model of training management based on a strategic–systemic–cybernetic approach.

Material and methods

The study was theoretical and modeling-based. Methods included analysis and synthesis of scientific literature, system analysis, cybernetic modeling, and graph theory. A directed graph $G=(V, E)$ was constructed, along with adjacency and reachability matrices, and topological sorting was applied to determine the hierarchical structure of the management system.

Results

A structural–functional model of training management for elite rugby teams was developed, integrating strategic, tactical-operational, and information-analytical levels. It was established that the comprehensive control subsystem occupies a central position in the system, concentrating the main information flows and acting as a mandatory transit node in decision-making processes. Graph analysis confirmed its dominant structural role and integrative function within the management system.

Conclusions

The proposed model enables the transition from fragmented and reactive management to an adaptive–predictive approach. The integration of systemic, cybernetic, and strategic principles within a graph-based framework improves the effectiveness, consistency, and scientific validity of decision-making in elite rugby training systems.

Key words: rugby, elite sport, training management, structural–functional model, cybernetic approach, graph theory, decision-making

Анотація

Квасниця О, Тищенко В, Верітов О, Зауренбек Б, Жунісбек Д, Соколова Л, Скрипченко І, Жолдошева А, Асаналієва М, Ференчук Б. Стратегічно-системно-кібернетична модель управління підготовкою елітної команди з регбі: графовий підхід

Обґрунтування і мета

Сучасне елітне регбі характеризується високою мінливістю ігрових ситуацій, значним фізичним навантаженням та стохастичними змагальними вимогами, що вимагає ефективних та адаптивних систем управління тренуваннями. Водночас, існуючі підходи часто розрізнені та не забезпечують інтеграції стратегічних, операційних та аналітичних компонентів. Метою дослідження була розробка та теоретичне обґрунтування структурно-функціональної моделі управління тренуваннями на основі стратегічно-системно-кібернетичного підходу.

Матеріал і методи

Дослідження було теоретичним та моделюючим. Методи включали аналіз та синтез наукової літератури, системний аналіз, кібернетичне моделювання та теорію графів. Було побудовано орієнтований граф $G=(V, E)$, матриці суміжності та досяжності, а також застосовано топологічне сортування для визначення ієрархічної структури системи управління.

Результати

Розроблено структурно-функціональну модель управління тренуваннями елітних команд з регбі, яка інтегрує стратегічний, тактико-операційний та інформаційно-аналітичний рівні. Встановлено, що комплексна підсистема управління займає центральне положення в системі, концентруючи основні інформаційні потоки та виступаючи обов'язковим транзитним вузлом у процесах прийняття рішень. Графовий аналіз підтвердив її домінуючу структурну роль та інтегративну функцію в системі управління.

Висновки

Запропонована модель забезпечує перехід від розрізненого та ситуативного управління до адаптивно-прогностичного підходу. Інтеграція системних, кібернетичних і стратегічних принципів у рамках графової структури підвищує ефективність, узгодженість та наукову обґрунтованість прийняття рішень в елітних системах тренувань з регбі.

Ключові слова: регбі, елітний спорт, управління тренуваннями, структурно-функціональна модель, кібернетичний підхід, теорія графів, прийняття рішень

Аннотация

Квасниця О, Тищенко В, Веритов О, Зауренбек Б, Жунисбек Д, Соколова Л, Скрипченко И, Жолдошева А, Асаналиева М, Ференчук Б. Стратегически-системно-кибернетическая модель управления подготовкой элитной регбийной команды: подход на основе графов

Обоснование и цель

Современный элитный регби характеризуется высокой изменчивостью игровых ситуаций, значительной физической нагрузкой и стохастическими требованиями к соревнованиям, что требует эффективных и адаптивных систем управления тренировками. В то же время существующие подходы часто фрагментированы и не обеспечивают интеграцию стратегических, оперативных и аналитических компонентов. Целью исследования было разработать и теоретически обосновать структурно-функциональную модель управления тренировками на основе стратегически-системно-кибернетического подхода.

Материал и методы

Исследование носило теоретический и модельный характер. Методы включали анализ и синтез научной литературы, системный анализ, кибернетическое моделирование и теорию графов. Был построен ориентированный граф $G=(V, E)$ вместе с матрицами смежности и достижимости, а для определения иерархической структуры системы управления была применена топологическая сортировка.

Результаты

Разработана структурно-функциональная модель управления тренировками элитных команд по регби, интегрирующая стратегический, тактико-оперативный и информационно-аналитический уровни. Установлено, что комплексная подсистема управления занимает центральное место в системе, концентрируя основные информационные потоки и выступая в качестве обязательного транзитного узла в процессах принятия решений. Графовый анализ подтвердил ее доминирующую структурную роль и интегративную функцию в системе управления.

Выводы

Предложенная модель обеспечивает переход от разрозненного и ситуативного управления к адаптивно-прогностическому подходу. Интеграция системных, кибернетических и стратегических принципов в рамках графовой модели повышает эффективность, согласованность и научную обоснованность принятия решений в системах тренировок элитных команд по регби.

Ключевые слова: регби, элитный спорт, управление тренировками, структурно-функциональная модель, кибернетический подход, теория графов, принятие решений

Introductions

Rugby, as a highly dynamic team sport, requires a comprehensive approach to training. At the same time, traditional models of training management are often fragmented and intuitive and do not correspond to the modern dynamics of competitive activity.

The relevance of the problem lies in the lack of an integrated, adaptive, and strategically oriented management model that would combine the physical, technical-tactical, medical-biological, and analytical aspects of training into a single managed system.

Modern elite rugby is characterized by a high level of physical contact, variability of game situations and stochastic competitive requirements, which significantly increases the importance of effective management of the training process. The effectiveness of teams is determined not only by the level of preparedness of athletes, but also by the quality of management decisions, the accuracy of information support and the ability of the system to adapt quickly to rapidly changing conditions of competitive activity.

Training management in rugby, despite the development of analytical technologies, often remains fragmented. The subsystems of physical, medical-biological, psychological and tactical training often operate in isolation, resulting in a gap between strategic goals and operational decisions and reduces the adaptability of the system.

The relevance of the problem is increasing by the nonlinear nature of loads, high risks of overloading and the need for operational tactical adjustments. Under such conditions, linear planning models are insufficient, which necessitates for integrative approaches to management.

In modern research on sports management, systemic, cybernetic and strategic approaches are used. The systemic approach provides structuring of training subsystems, the cybernetic approach contributes to control and feedback mechanisms, and the strategic approach defines long-term development goals. However, their application is mostly isolated and that limits the effectiveness of management in highly dynamic sports.

In this regard, the integration of these approaches into a single management model, in which complex control acts as an information and analytical core, ensuring the coordination of decisions among the strategic, tactical-operational and analytical levels, is of particular importance.

The solution to this scientific problem necessitates the theoretical and methodological substantiation and modeling of a modern management system for the training of elite rugby teams based on the integration of strategic, systemic and cybernetic approaches.

Modern training of elite rugby teams is considered as a multi-level system, the effectiveness of which is determined not only by the quality of individual training influences, but also by the consistency of strategic planning, operational control, analytical support and timely correction of management decisions. In the scientific literature there are several leading directions of understanding this issue.

Within the framework of the systemic approach, sports training is interpreted as a holistic, hierarchically organized system of interconnected components, in which the result is formed not by individual elements, but by the nature of the connections between them. In works devoted to the general theory of sports training, the need to consider the training process as a multi-component structure, including goals, means, loads, control, adaptation and recovery, is emphasized. It is the systemic approach that creates a methodological basis for structuring training subsystems and determining their functional hierarchy. At the same time, its possibilities are mainly focused on describing the organization of the system, while the mechanisms of operational response to changes in the state of athletes and the dynamics of the competitive environment are not sufficiently disclosed. The classic works on the theory of sports training by Platonov, Issurin and Bompa laid just such a systemic vision of the training process [1-3]. However, while these classical frameworks provide a robust theoretical foundation, contemporary elite sport increasingly requires their integration with data-driven and adaptive approaches, reflecting the shift toward real-time decision-making and complex system interactions.

The cybernetic approach focuses on the mechanisms of management, information circulation, control and feedback. In modern elite sport, the feedback is considered a key condition for timely correction of training, and the use of monitoring and tracking systems is regarded as the means of supporting objective decision-making regarding load, recovery and risks [4]. Reviews of team sports show that data from tracking systems can be used to describe, plan, and monitor external load, but their practical value is determined not by the fact of collecting information itself, but by its integration into logic of management [5, 6]. Similarly, systematic feedback in training can enhance the adaptive effect and increase the effectiveness of the decisions of a coach. Thus, the cybernetic approach provides a dynamic circuit of “control – analysis – correction”, but without a system architecture and strategic framework it is often reduced to fragmentary monitoring of individual indicators [7, 8].

Recent studies emphasize the growing role of wearable technologies (e.g., GPS tracking systems, inertial sensors, and collision monitoring devices) in elite rugby. These tools enable real-time assessment of external and internal load, providing a basis for adaptive training adjustments and individualized load management strategies [9, 10]. These technologies are no longer limited to descriptive monitoring but are increasingly integrated into decision-support systems, enabling dynamic load adjustment based on real-time indicators such as player tracking metrics, collision frequency and neuromuscular fatigue markers.

The strategic approach is associated with long-term goal-setting, coordination of resources, stages of preparation and models for achieving sports results. Studies of modern performance preparation models emphasize that an effective training system should combine work on different time scales – from daily practice to long-term development of athletes and a team. Such approaches focus a coach not only on the current state of the performers, but also on the prospective construction of the process, taking into account the competitive calendar, environmental constraints and expected results. At the same time, the strategic approach often remains insufficiently formalized: it outlines the vector of development, but does not always contain a clear set of tools for implementing, monitoring and adapting decisions in real time [11-13].

A separate group is the studies in which team sports and sports organizations are considered as complex adaptive systems. Such works emphasize hierarchical organization, multilevel interactions, circular causality and the dependence of the result on the context, which is especially important for highly dynamic sports. For team games, this means that training management cannot be reduced only to a linear sequence of “plan – execution – evaluation”, but requires the integration of structural organization, analytics and adaptive regulation [14, 15]. In line with these perspectives, contemporary research increasingly adopts an ecological dynamics framework, which emphasizes the interaction between athletes and their environment. This approach shifts the focus from rigid, pre-defined training structures toward adaptive, context-dependent performance development, where behavior emerges from continuous interactions within the system. Such a perspective reinforces the need for integrated and flexible management models capable of responding to the dynamic nature of elite rugby. This paradigm fundamentally challenges linear and reductionist training models, emphasizing that performance emerges from continuous athlete–environment interactions, thereby requiring flexible and non-linear management systems.

For rugby, this problem is of particular importance, as the game is characterized by high contact, significant variability of game situations, a combination of physical, technical-tactical and psycho-functional requirements, as well as the need for operational use of analytical information in training and competition processes. Reviews about performance analysis of rugby union and elite rugby league confirm that analytics has already become an important part of practice, but existing approaches are mainly focused on individual aspects of assessment or support for coaching decisions, rather than on a holistic management model that would combine the strategic, systemic and cybernetic levels into a unified architecture [16, 17].

Thus, the analysis of scientific literature has shown that the systemic approach provides a structural understanding of training, the cybernetic approach – control and feedback mechanisms, and the strategic approach – a long-term logic of development. However, in modern research, these approaches are considered mostly in isolation. Despite the existing scientific achievements, there are no works in which the systemic, cybernetic and strategic approaches would be integrated into a single formalized management model for the training of elite rugby teams. It is this scientific niche that has determined the need to develop a structural-functional model of training management of elite rugby teams, based on the strategic-systemic-cybernetic approach [18].

Purpose: is theoretical and methodological justification and development of a structural and functional model of elite rugby teams training management based on the strategic-systemic-cybernetic approach.

Material and methods

The study is theoretical and modeling-based in nature. Empirical observations were used as a supplementary method to support the interpretation of management processes in elite rugby teams.

Research design: analysis and synthesis of scientific sources in the field of sports training theory, systems analysis, management cybernetics and strategic management. Systems analysis was used to allocate the structural components of the training process and to determine the hierarchy of management subsystems.

Modeling approach. To represent the training process as a complex hierarchical system, systemic and cybernetic (for control and feedback mechanisms) modeling was applied. Mathematical and graph modeling included the construction of a directed graph

$$G=(V,E)$$

where: G – directed graph representing the training management system; V – set of vertices (subsystems); E – set of directed edges representing information and control interactions.

In the proposed model, vertices correspond to the main functional subsystems (such as training, medical and biological support, psychophysiological monitoring, and the analytical module), while edges reflect the information and control interactions between them.

To better understand the role of each subsystem, the number of incoming and outgoing connections was analyzed (in-degree $\text{deg}^-(v)$ and out-degree $\text{deg}^+(v)$). This makes it possible to identify key elements of the system that concentrate data streams, in particular the comprehensive control subsystem.

The adjacency matrix $A = [a_{ij}]$ was used to describe direct connections between subsystems.

$$A = [a_{ij}] \quad \text{Formula (1)}$$

where: A – adjacency matrix representing direct connections between subsystems; a_{ij} – element indicating the presence (1) or absence (0) of a direct connection between subsystem i and subsystem j.

In addition, the reachability matrix $R = [r_{ij}]$ was applied to determine whether information can be transmitted between subsystems through direct or indirect links.

$$R = [r_{ij}] \quad \text{Formula (2)}$$

where: R – reachability matrix (transitive closure of adjacency matrix A); r_{ij} – element indicating the existence (1) or absence (0) of a direct or indirect path between subsystems i and subsystem j.

This allows a clearer understanding of how information circulates within the system and supports decision-making processes.

Graph theory methods. Graph-based modeling was selected as it allows formal representation of complex interactions among management subsystems. Adjacency and reachability matrices were used to analyze structural connectivity and information streams. Topological sorting (the Demukron algorithm) was applied to determine the hierarchical structure and sequence of information processing.

Results

The adjacency matrix (Fig. 1) was used to quantify the direct structural connections between control subsystems and to identify the nodes with the highest level of connectivity. The analysis of the rows and columns of matrix A showed that the vertices, associated with complex control, were characterized by high total connectivity, which corresponds to their high information centrality and minimization of the length of information transmission paths between the strategic and tactical-operational levels of management.

Table 1
Adjacency matrix $A = [a_{ij}]$ representing direct connections between subsystems

From \ To	V ₂	V ₃	V ₄	V ₅	V ₆	V ₇	V ₈	V ₉	V ₁₀	V ₁₁	V ₁₂	V ₁₃	V ₁₄	V ₁₅	V ₁₆
V ₁	1	1	1	0	0	0	0	0	0	0	0	0	1	0	1
V ₂	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
V ₃	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0
V ₄	0	0	0	1	1	0	1	1	1	0	0	0	0	1	0
V ₅	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0

From \ To	V ₂	V ₃	V ₄	V ₅	V ₆	V ₇	V ₈	V ₉	V ₁₀	V ₁₁	V ₁₂	V ₁₃	V ₁₄	V ₁₅	V ₁₆
V ₆	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0
V ₇	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0
V ₈	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0
V ₉	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0
V ₁₀	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
V ₁₁	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
V ₁₂	1	0	1	1	1	1	1	1	0	0	0	1	0	0	0
V ₁₃	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
V ₁₄	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
V ₁₅	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0
V ₁₆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Notes: Interpretation of model components (V_n): V₁: strategic planning (goal setting and resource allocation); V₂–V₄: nodes forming general management decisions, following the information-analytical block according to topological sorting; V₅–V₉: functional training subsystems (training process; medical and biological support; psychophysiological monitoring; technical and tactical preparation; analysis of competitive activity); V₁₀: comprehensive control (CC) – central information-analytical core of the system; V₁₁: database (storage and systematization of incoming information); V₁₂: analytical module (data processing for decision-making support); V₁₃: feedback mechanisms (closing the control loop); V₁₄–V₁₆: external influencing factors (regulatory, scientific, and socio-economic conditions) affecting strategic decisions but not directly involved in operational feedback cycles.

The adjacency matrix $A = [a_{ij}]$ provides a quantitative representation of direct structural connections between management subsystems. In this matrix, $a_{ij} = 1$ indicates the presence of a direct connection between subsystems, whereas $a_{ij} = 0$ indicates the absence of such a connection.

The distribution of unit values (1) across rows and columns reflects the level of connectivity of each subsystem within the overall structure. Subsystems characterized by a higher number of connections can be interpreted as structurally significant elements of the management system, due to their greater involvement in information exchange and coordination processes.

The analysis of the adjacency matrix revealed that the node corresponding to comprehensive control (V₁₀) has the highest degree of connectivity, receiving inputs from multiple subsystems and redistributing information across the system. This confirms its role as a central coordination node ensuring efficient information exchange between strategic and tactical-operational levels.

The adjacency matrix $A=[a_{ij}]$ showed that the vertex V₁₀ (CC as IS) has a high input degree (information from trainings, medical, psychological subsystems) and a high output degree (data transfer to the database, analytics, feedback): the vertex V₁₂ (analytical module) is the second most connected, integrates data for decision-making; the vertex V₁₃ (feedback) closes the control circuit; according to the topological sorting of Demukron, the nodes V₁₀–V₁₂–V₁₃ will be located before the levels V₁–V₄, that is, they will form the informational pre-support of management (Table 1).

Additional use of Reachability matrix R (transitive closure of adjacency matrix A), which reflects the availability of directed paths among the vertices of the graph, made it possible to establish that most management chains pass through the subgraph G_{KK}. This indicates that integrated control plays the role of a mandatory transit node in the process of forming managerial influences and feedback (Figure 2). The reachability matrix was constructed to analyze directed information pathways within the management system. The reachability matrix demonstrated that most control pathways pass through the comprehensive control subsystem, confirming its role as a central integration node.

In particular, the vertex V₁₀ (complex control) is characterized by high reachability both in terms of incoming and outgoing connections, receiving data from subsystems V₅–V₉, V₁₁–V₁₂, V₁₅ and transmitting information to the coaching staff, management structures and the analytical module. This reveals its integration role in the system. At the same time, the vertices of the external level (V₁₄–V₁₆)

influence the system, but do not always participate in closed feedback circuits, that reflects the real conditions of training management. Reachability matrix R looks like this (under the condition of transitive closure) (Table 2).

Table 2

Reachability matrix $R = [r_{ij}]$ representing the accessibility of directed paths between subsystems for the analysis of information and control pathways

From \ To	V ₁	V ₂	V ₃	V ₄	V ₅	V ₆	V ₇	V ₈	V ₉	V ₁₀	V ₁₁	V ₁₂	V ₁₃	V ₁₄	V ₁₅	V ₁₆
V ₁	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V ₂	0	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1
V ₃	0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1
V ₄	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
V ₅	0	0	0	0	1	1	1	1	1	1	1	1	1	0	1	1
V ₆	0	0	0	0	0	1	0	0	1	1	1	1	1	0	1	0
V ₇	0	0	0	0	0	0	1	0	1	1	1	1	1	0	1	0
V ₈	0	0	0	0	0	0	0	1	1	1	1	1	1	0	1	0
V ₉	0	0	0	0	0	0	0	0	1	1	1	1	1	0	1	0
V ₁₀	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0
V ₁₁	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
V ₁₂	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
V ₁₃	0	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1
V ₁₄	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
V ₁₅	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0
V ₁₆	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Notes: interpretation of the model components (V_n) is provided above (see Table 1).

The reachability matrix $R = [r_{ij}]$ reflects the existence of direct and indirect paths between all vertices of the graph. In this matrix, $r_{ij} = 1$ indicates that information can be transmitted from subsystem i to subsystem j through one or more intermediate nodes, whereas $r_{ij} = 0$ indicates the absence of such a pathway.

This representation makes it possible to analyze the integrity of information chains, identify key transit nodes, and evaluate the overall connectivity of the management system. Graph modeling revealed a hierarchical structure of the elite rugby team training management system. The system is organized at three interconnected levels: a strategic level, responsible for setting goals and allocation of resources; a tactical-operational level, which ensures the planning and implementation of training and competition events; and an information-analytical level, which integrates data streams and supports decision-making through feedback mechanisms.

The identified functional roles of each management level and their contribution to the integrity of the system are summarized in Table 3.

Table 3

Functional roles of management levels in the proposed model

Management level	Functional role	Resulting effect
Strategic	Goal setting and resource allocation	Long-term coherence

Tactical-operational	Implementation of training and competition	Process execution
Information-analytical	Integration, analysis and feedback	Adaptive–predictive control

The presented distribution confirms the hierarchical differentiation of management functions and highlights the integrative role of the information-analytical level in ensuring adaptive and predictive control.

The functioning of the complex control as the information management system gets a formalized representation in the form of a directed graph,

$$G = (V, E),$$

which describes the structure and dynamics of a team training management. The set of vertices V represents the structural control subsystems and information and analytical components, and the set of arcs E represents the directed information, control and feedback links among them. Such a representation allows us to consider training management as a discrete dynamic system with structurally defined information streams. In terms of the graph model, the vertices corresponding to the complex control, analytical module and feedback mechanisms and are characterized by increased information centrality, since it is through them that the main data streams between the strategic and tactical-operational levels of management pass. The arcs of the graph reflect the control and information interactions that ensure the closure of the cybernetic circuits “analysis – decision – correction”. Thus, the directed graph $G=(V,E)$ not only illustrates the structural organization of the control system, but also substantiates the key role of complex control as an information core that integrates data from different subsystems, transforms them into control signals and ensures adaptability and consistency of management decisions. Formalization of control in the form of a graph structure allows us to move from a descriptive idea of control to a mathematically based model of the functioning of the information system for managing the training of elite rugby teams.

Thus, graph-based analysis provides a formal justification for the transition from structural description to system-level representation. The identified patterns of connectivity, reachability, and centrality allow us to synthesize a single structural-functional model of learning management that integrates all subsystems within a single coordinated structure (Figure 1).

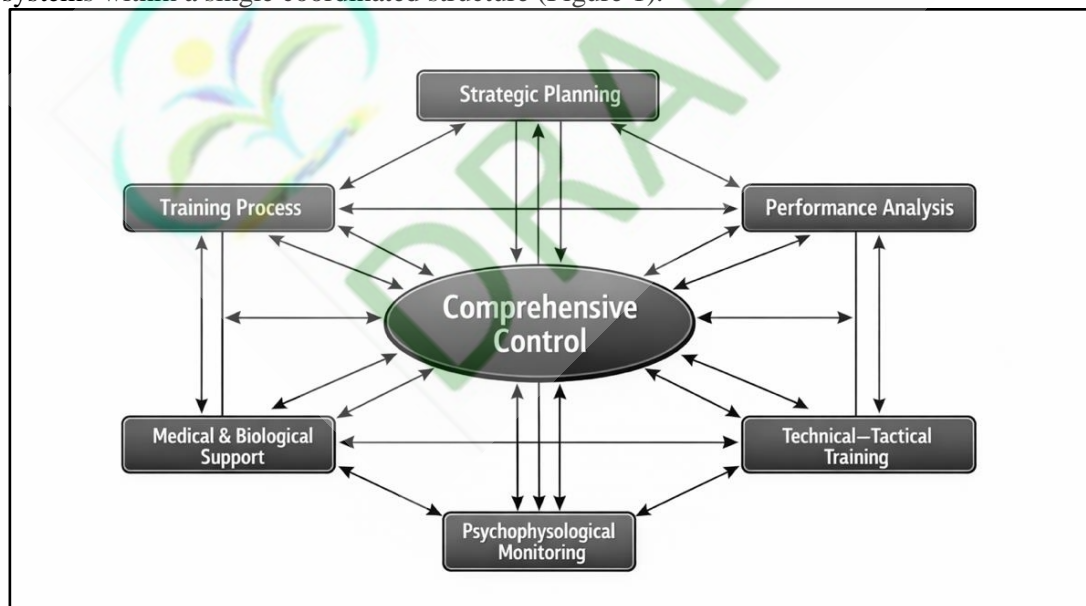


Figure 1. Structural–functional model of training management based on graph representation

The vertices of the graph correspond to the key training subsystems, including strategic planning, training process, medical and biological support, psychophysiological monitoring, technical and tactical training and analysis of competitive activity.

The topology of the graph indicates the dominant position of the “complex control” vertex, through which the main part of the information streams passes. This makes it possible to consider it as a central element of the system, providing integration of disparate data and support of coordinated management decisions at all levels.

Such an organization of the system enables a transition from fragmented management to the adaptive and prognostic model is capable to respond effectively to the dynamics of the training and competition process.

An information-analytical subgraph is formed within the graph

$$G_{\text{KK}}=(V_{\text{cc}}, E_{\text{cc}}).$$

which includes vertices corresponding to complex control, database and analytical module. The analysis of the structural characteristics of this subgraph indicates its dominant role in the overall control architecture. In particular, vertices $v \in \text{VKK}$ are characterized by increased values of input and output degrees

$$\text{deg}-(v) \text{ ((number of incoming links)) } i \text{ deg}+(v) \text{ (number of outgoing links),}$$

which indicates the concentration of the main information streams in them and establishes their function as data integration nodes.

It is through the information-analytical subgraph that the main information streams pass, combining the strategic and tactical-operational levels, ensuring the coordination of management decisions and the closure of feedback. The use of topological sorting procedures confirms the hierarchical arrangement of the vertices of complex control at the early stages of the information processing sequence, which provides informational pre-support for decision-making. In the cybernetic interpretation, this means that it is through the specified subgraph that the key feedback circuit are closed, which ensure the adaptability and stability of the management system.

A formalized analysis of the connectivity and accessibility of system elements confirmed that most managing chains pass through the complex control subsystem, which indicates its function as a mandatory transit node in the process of forming management influences and feedback.

Graph analysis showed that the information and analytical block, represented by a complex control subsystem and associated data and feedback modules, forms the structural core of the control system. This subsystem concentrates the largest number of input and output information streams, ensuring the integration of training, medical and biological, psychological and competitive data into a single decision support system. Such a configuration allows early detection of maladaptive tendencies and supports adaptive and predictive regulation of the training process in conditions of stochastic competitive requirements.

The hierarchical ordering of the control structure demonstrated that the integrated managing subsystem occupies a central position between operational training activities and strategic decision-making. Its role in providing informational pre-training of management decisions and closing the cybernetic feedback cycle, which is important for maintaining system stability in high-contact team sports such as rugby.

External regulatory, scientific, and socio-economic factors were identified as contextual influences that modulate strategic decision-making without direct involvement in operational feedback cycles, reflecting the real limitations of elite team training.

As a result of graph modeling, a hierarchical structure of the management system was established, which includes strategic, tactical-operational, and information-analytical levels, integrated through feedback mechanisms. Such structure ensures the coordination of goals, resources, and training influences within a single managed system.

Algorithmic analysis of the management hierarchy confirmed that complex control is located in the central layer of the system, providing informational pre-support for management decisions and closing cybernetic feedback loops.

As a result of the modeling, the following was established:

- the structural configuration of the training management system for elite rugby teams in the form of a directed graph $G=(V, E)$;
- the dominant role of complex control as the structurally central information and analytical core of the system;
- the presence of integrated feedback circuits among the strategic, tactical-operational and analytical levels of management;
- the possibility of transitioning from a reactive to an adaptive-predictive model of training process management.

Summarizing the results obtained, it should be noted that the proposed model formalizes the management of the training of elite rugby teams as a holistic hierarchically organized information-driven system. It is the presence of an integrated information-analytical core that ensures the coordination of

strategic goals, tactical and operational decisions, and feedback mechanisms, which creates the prerequisites for the stable functioning of the system in conditions of high variability and stochasticity of competitive activity.

The results are interpreted taking into account the specifics of rugby as a high-contact sport with a complex structure of game activity and do not provide for direct transfer to sports with other models of competitive load without appropriate adaptation.

Discussion

The novelty of this study lies in the integration of system, cybernetic, and strategic approaches into a unified graph-based model of training management, providing a formalized representation of information exchange and decision-making processes.

The obtained results are consistent with modern ideas about team sports as complex adaptive systems in which the result is formed due to the interaction of many interconnected components. These findings are also consistent with ecological dynamics approaches, which view performance as an emergent property of interactions between the athlete, task, and environment, further supporting the need for adaptive and integrated training management systems. Thus, in the studies of Duarte et al. (2012) showed that the effectiveness of game activity is determined not by individual indicators, but by the coordination dynamics of the system, which fully corresponds to the hierarchical and interconnected structure of training management identified in our study [19].

The research results are also related to modern approaches to monitoring and analysis in team sports [20-22]. Some authors emphasize that the use of tracking technologies and analytical systems allows to obtain objective data on training and competition activities [23-25]. However, in these works, the focus is on the collection and interpretation of data, while in the present study, their structural integration into a single control system, where complex control acts as a central information-analytical node, is additionally substantiated.

An important aspect is compliance with modern concepts of cybernetics, according to which complex systems are functioning on the basis of mechanisms of feedback and information regulation [26, 27]. Thus, Lv et al. (2025) [28] showed that the feedback increases significantly the effectiveness of training, and Ranaweera et al. (2022) [29] showed that the management of athletes' training is based not on individual decisions, but on the information circulation system. Differing from the specified approaches, this study expands the existing approaches, moving from the identification of the inefficiency of information streams to the development of a unified and mathematically based training management model capable of integrating data, feedback mechanisms, and decision-making processes within a single structure. We have proven that feedback mechanisms have not only functional, but also structural significance, being built into the control system through closed circuits in the graph model. In accordance with these provisions, management of the training process should be considered as a continuous cycle of information processing and adaptive correction, which is reflected in the proposed model.

The obtained results are also agreed with the research aimed at the application of artificial intelligence and machine learning methods in the analysis of sports activities. Modern reviews show that predictive analytics allows you to predict the results and risks of injury [30-32]. At the same time, these works lack a formalized representation of the management structure into which such models are integrated. In this study, such a structural basis is proposed, which allows considering analytical tools as a part of a single decision-making system. In recent years, machine learning approaches have shifted from traditional statistical models to deep learning architectures, including recurrent neural networks (RNN) [33, 34], long short-term memory (LSTM) models [35, 36] and ensemble learning approaches (e.g., XGBoost) [37, 38], which enable the identification of non-linear relationships between workload parameters and injury risk. These models significantly enhance predictive accuracy and allow early detection of maladaptive states in athletes.

From the standpoint of the classical theory of sports training, the research results develop the provisions of periodization concepts [39-41], which describe the temporal organization of the training process. Unlike to them, the proposed model adds the temporal structure with a spatial-structural and information dimension, allowing to analyze not only the sequence of loads, but also information streams, control mechanisms and interconnections between subsystems.

In the context of research directly devoted to team game sports, it was found that the existing works are mainly directed to the analysis of game indicators, physical qualities and competitive activity

[42, 43]. Despite the high information content of these works, they are predominantly analytical in nature and do not offer a comprehensive model for managing the training process.

Furthermore, the results are consistent with the studies examining the effectiveness of multidisciplinary athlete support teams, which highlight the need for coordination among different specialists [44, 45]. In the proposed model, this coordination is implemented through the information and analytical core of the system, which ensures the consistency of management actions at all levels.

The results of the study are also supported by research on the psychophysiological characteristics of athletes. It has been shown that the functional state and psychophysiological characteristics of athletes are highly variable and depend on a variety of factors, including training load, playing role, and physiological characteristics [46-49]. This confirms the need for continuous monitoring and adaptation of the training process, which in the framework of this study was implemented through a comprehensive control system.

Similarly, the modern research in the field of sports analytics aim to integrate various indicators and identify patterns in gaming activity [50, 51]. However, they lack a formalized representation of a management system that combines the processes of analysis, decision-making and feedback.

Thus, our data do not contradict existing scientific data, but rather complement it, demonstrating that effective management of rugby team training requires the integration of systemic, cybernetic, and strategic approaches within a single structural-functional model.

The results obtained in this study expand these approaches by shifting the focus from the analysis of individual indicators to the study of training management, that allows to integrate the heterogeneous data into a single decision-making system [52, 53].

Further support for these findings can be found in contemporary research on the application of graph methods and systems analysis in team sports. For example, Russo et al. (2025) demonstrated that graph models are effectively used to analyze player interactions and the structure of game actions [54]. However, these approaches are limited to the analysis of competitive activity and do not extend to training management. In contrast, in this study, a graph model is used to formalize a training management system, allowing us to describe not only interactions but also information streams and management links between subsystems.

The results of the study also relate to the studies examining team sports from a systems perspective. In particular, Piepiora et al. (2025) emphasize the need for a holistic analysis of the team as an interconnected system in which individual elements cannot be considered in isolation [55]. However, these studies are primarily conceptual in nature and do not contain formalized management models, whereas in this work the systems approach is implemented through a structural-functional model.

Similar ideas for integrating various components of training are presented in the work of Kannan (2026), where the need for a synergistic combination of training effects within the framework of periodization models is substantiated [56]. However, this approach is limited to the organization of training loads information management and feedback mechanisms and does not encompass information management and feedback mechanisms. In contrast, the proposed model integrates structural organization, control mechanisms and strategic planning into a single management system.

Thus, whereas existing studies that consider either individual aspects of analysis or the conceptual foundations of the systems approach, this study proposes a formalized training management model based on the integration of graph analysis, cybernetic principles and strategic planning.

This confirms that the system operates through centralized information flows, reinforcing the role of comprehensive control as a mandatory transit node. The developed strategic–systemic–cybernetic model of training management for elite rugby teams can be directly used by the coaching staff as a tool for integrated planning, monitoring, and adjustment of the training process. From a practical perspective, the proposed graph-based model should not be interpreted solely as a theoretical abstraction, but rather as a formalized representation of real management processes in elite rugby teams.

First, the model addresses the problem of fragmentation between specialized subsystems. In practice, medical, coaching, and analytical staff often operate with partially disconnected information. The proposed structure integrates these components through a unified information-analytical core, ensuring timely data exchange and coordinated decision-making.

Second, the central position of the comprehensive control subsystem contributes to the objectification of management decisions. By concentrating multiple coordination mechanisms within a single analytical node, the model reduces reliance on intuitive judgments and supports evidence-based adjustments of the training process.

Third, the presence of closed feedback loops within the system allows early identification of maladaptive responses, including signs of overtraining or performance decline. This creates conditions for proactive intervention and continuous regulation of athlete preparation. Thus, the model can be interpreted as a “digital shadow” of the training management system, reflecting both its structural organization and dynamic information processes.

At the strategic level, the model supports long-term goal setting and resource allocation, ensuring alignment between training processes and development priorities. At the tactical-operational level, it enables planning and adjustment of training cycles based on real-time data from the comprehensive control subsystem. The integration of multidimensional data into a unified information platform allows coaches to make decisions based on system-level interactions rather than isolated indicators.

The model enables early detection of negative trends, prediction of training effects, and adaptive adjustment of training processes.

Thus, the model transforms training management from an intuitive-reactive approach to a system-based and predictive one, increasing decision-making efficiency under conditions of high variability in elite rugby.

In the proposed model, comprehensive control is interpreted as an integrated information-analytical system rather than a separate evaluation tool. It ensures continuous data collection, integration, and transformation into management decisions, forming closed feedback loops between strategic, tactical-operational, and analytical levels. This shows its role as a system-forming element that supports adaptive and predictive regulation of the training process.

The implementation of the model shifts training management from a linear and fragmented approach to an integrated system-based framework. It enhances planning, control and decision-making by incorporating real-time data and predictive analytics.

From the perspective of graph theory, the dominant role of complex control in the management system can also be interpreted through centrality indicators. In particular, high values of (degree centrality) indicate the concentration of information flows in the vertices corresponding to complex control and the analytical module. Potentially increased (betweenness centrality) indicates their role as transit nodes through which most of the management paths between the strategic and tactical-operational levels pass. High (closeness centrality) of such vertices reflects the minimum average length of paths to other elements of the system, which ensures the efficiency of the formation of management decisions. The combination of these characteristics demonstrates the status of complex control as the information-analytical core of the management system.

Thus, from a mathematical point of view, complex control within the digraph model $G=(V,E)$ acts as a structurally central information and analytical core of the system. Its removal or reduction of its functional role would lead to the gap of oriented control paths, a decrease in the connectivity of the graph and a loss of controllability of the system, which confirms its system-forming value in the model of management of the training of elite rugby teams.

The interpretation of the obtained results shows that the presence of complex control as an information and analytical core ensures coordinated interaction between the strategic, tactical-operational and analytical levels of management. Due to this, managerial influences are formed not fragmentarily, but on the basis of a systematic analysis of the current state and the dynamics of adaptation processes, which increases the stability and predictability of training.

From a managerial point of view, the modeling results confirm that complex control serves as a mechanism for coordinating management decisions over time and across hierarchy levels, which allows for a transition from reactive management to adaptive-predictive management, when the correction of the training process is carried out not after the occurrence of negative consequences, but at the stage of formation of risks of overload or reduction in efficiency.

The findings not only align with existing research but also extend it by providing a formalized representation of training management as an integrated system. The proposed model shifts the focus from isolated analysis of performance indicators to the structural organization of decision-making processes, demonstrating that effective management in elite rugby requires the integration of systemic organization, cybernetic feedback and strategic planning within a unified framework.

A limitation of this study is its theoretical nature and lack of empirical validation. Therefore, future research should focus on implementing the proposed model in real training environments and evaluating its practical effectiveness.

Thus, the proposed model may be considered as a unifying framework that integrates classical approaches with modern data-driven technologies, including wearable monitoring systems, machine

learning-based predictive analytics and ecological dynamics principles. This integration enables a transition from descriptive and reactive management toward a proactive, adaptive and intelligent training system.

Conclusions

A structural-functional model of training management for elite rugby teams was developed based on the integration of system, cybernetic, and strategic approaches within a unified framework.

Graph-based modeling using directed graphs and matrix representations (adjacency and reachability) confirmed the central role of comprehensive control as a structurally dominant information-analytical hub within the management system.

The model formalizes training management as a hierarchical and dynamically interconnected system, allowing quantitative analysis of information flows, feedback loops, and decision-making pathways.

From an applied standpoint, the proposed model provides a basis for transitioning from reactive to predictive management of the training process. It enables coaching staff to anticipate changes in athletes' functional state and adjust training loads proactively rather than responding to already manifested outcomes.

The use of graph theory offers a formal tool for assessing the stability and integrity of the management system. In particular, the central role of the comprehensive control subsystem indicates that disruption of this node would significantly reduce system coherence and controllability.

Although the model is developed with consideration of the specific demands of elite rugby, characterized by high variability and complexity, it establishes a general framework for designing modern, integrated and data-driven training management systems in team sports.

Conflict of interest

The authors declare that there is no conflict of interest in this study.

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Received: 2026-02-05. Accepted: 2026-04-12. In press: 2026-04-13. Published: 2027-06-19