Embodied Autonomous Intelligence for On-Demand Manufacturing: A RoboCup Industrial Workshop Proposal

Marco Masannek* Christoph Steup* Asad Norouzi† Wataru Uemura‡

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Abstract

This paper presents a workshop concept for the Smart Manufacturing League (SML), the new RoboCup Industrial competition format starting in 2026. By merging the two established leagues RoboCup Logistics League (RCLL) and RoboCup@Work, the *Embodied Autonomous Intelligence Workshop (EAI-WS)* proposes a unified vision of an autonomous manufacturing environment in which products are assembled and recycled on-demand, supporting more sustainable and adaptive production paradigms.

The *EAI-WS* restructures former league tasks to better reflect contemporary research challenges in robotics while improving transparency, solution openness, and comparability across team performances. To enable continuity for established teams, the competition is organized into three complementary tracks: planning, warehouse, and workbench. These tracks allow teams to specialize in familiar research domains while gradually exploring new areas without compromising competitive participation. In particular, the newly introduced workbench track benchmarks manipulation dexterity during assembly and recycling, addressing high-precision handling of components, tools, and finished products. The planning and warehouse tracks build upon and extend the core elements of the former leagues—namely action scheduling, navigation, and real-world manipulation—towards more realistic and integrated scenarios.

The proposed technical regulations relax many previous hardware constraints, encouraging creative and emerging system designs, such as humanoid robots, while maintaining practical feasibility for teams and event organizers. A redesigned scoring and competition structure captures both specialization and system-level autonomy, allowing the identification of best-in-class solutions as well as overall league performance. To lower entry barriers for new and inexperienced teams, the concept introduces flexible mechanisms such as human–robot interaction and inter-team collaboration, enabling participation without undermining the integrity of the competition. A tiered competition design with gradually increasing complexity further supports sustainable team development and long-term research progress.

With a focus on providing a concrete participation framework for the 2026 transition year, this paper outlines the vision of the *EAI-WS* and details an exemplary scenario, technical regulations, competition design, and event structure.

*RoboCup@Work Executive Committee
†RoboCup@Work Trustee
‡RoboCup Logistic League Executive Committee

1 Introduction

The RoboCup Smart Manufacturing League (RCSML or SML) is RoboCup's new industrial competition format from 2026 onwards. It aims to merge two established leagues — RoboCup Logistics League (RCLL) and RoboCup@Work — in order to overcome limitations of outdated competition elements and to formulate a future-proof research environment addressing the challenges of Industry 5.0 and beyond.

As part of this transition, the RCLL Committee drafted and published an initial vision during the RoboCup Symposium 2025 [1], with the intention of providing a baseline for subsequent merger discussions. The vision identified several core capabilities for intelligent robotic systems in modern production facilities and proposed a competition concept centered around flexible, on-demand production using small polymer building blocks as product components. Three tracks — production logistics, assembly, and humanoid manufacturing — were introduced, each associated with dedicated tasks, workspaces, and specialized hardware designs. Through predefined interfaces and handover strategies, successful task execution required tight collaboration between heterogeneous robotic agents, thereby emphasizing human–robot and robot–robot interaction as central elements of the league.

While many of these ideas were welcomed by the Executive Committee of the RoboCup@Work league, further discussions in late 2025 revealed several open questions regarding task complexity, practical feasibility, participation costs, entertainment value, and openness to solutions. In particular, concerns were raised about mandatory hardware abstractions, strict task separation, and the risk of constraining future innovation by predefining system roles and interaction patterns too rigidly.

In response, the *Embodied Autonomous Intelligence Workshop (EAI-WS)* concept was developed as an alternative workshop-oriented participation format for the SML transition phase. The *EAI-WS* aims to preserve the core philosophy of a sustainable, demand-driven smart factory aligned with Industry 5.0, while adopting a solution-agnostic and intentionally non-prescriptive design. Rather than enforcing specific robot roles or hardware architectures, the workshop defines shared goals, constraints, and evaluation criteria, allowing teams to explore diverse system designs ranging from single, highly capable robots to heterogeneous fleets.

The *EAI-WS* emphasizes integrated autonomy, embodied decision-making, and flexible execution strategies, with the explicit intention of allowing efficient solutions to emerge naturally from system capabilities rather than being dictated by league design. By maintaining low entry barriers and enabling gradual scaling of complexity, the workshop format supports both new and experienced teams while fostering comparative insights across different manufacturing abstractions.

Given the transitionary nature of the 2026 season, this document is explicitly framed as a workshop concept rather than a finalized or binding league rulebook. Its purpose is to set expectations for experimental on-site activities, facilitate structured exploration of embodied autonomous intelligence in smart manufacturing scenarios, and provide a foundation for iterative refinement through practical experience at upcoming RoboCup events.

2 Vision

The *Embodied Autonomous Intelligence Workshop (EAI-WS)* aims to transfer knowledge and research advances from the former RoboCup industrial leagues into a unified and forward-looking robotic vision for modern production facilities. The overarching goal is to explore flexible and fully autonomous factory environments that move beyond traditional mass production—where goods are manufactured in large batches and stored over long periods—towards on-demand manufacturing paradigms. By enabling robotic systems to autonomously produce, assemble, and recycle products as required, the workshop promotes sustainable, resource-efficient, and adaptive production concepts (see Fig. 1).

Figure 1: *Embodied Autonomous Intelligence Workshop (EAI-WS)*: Illustration of a future on-demand production and recycling facility enabled by embodied autonomous intelligence in robotic systems.

Covering established and emerging research areas such as robotic intralogistics, advanced object manipulation, multi-robot coordination, and planning and optimization, the *EAI-WS* seeks to translate real-world industrial challenges into an engaging research, benchmarking, and competition framework. Rather than prescribing specific solution strategies, the workshop emphasizes outcome-oriented tasks that allow diverse robotic approaches to be evaluated under shared constraints.

2.1 Long-Term Vision

The long-term vision of the *EAI-WS* is to advance robotics research toward *open and unsolved problems relevant to future smart manufacturing scenarios*. The competition deliberately targets robotic capabilities that are currently underexplored, technologically immature, or economically infeasible at industrial scale, but are expected to gain relevance in the coming years.

Industrial partners are consulted to help identify meaningful application contexts and challenges, while the competition environment remains abstracted, reproducible, and affordable. This balance enables systematic benchmarking and comparative evaluation of emerging methods without the complexity, risk, and cost associated with full industrial deployment.

The envisioned scenarios emphasize *heterogeneous robotic tasks* under realistic operational constraints, including robust navigation in shared spaces, precise manipulation under uncertainty, human–robot interaction (HRI), cross-vendor and cross-team collaboration, and large-scale planning and optimization. While specialized solutions are often effective for individual sub-problems, generalized and integrated approaches are considered equally important to foster flexibility, robustness, and reusability across tasks and environments. [1]

Consequently, the competition structure follows a dual philosophy: distinct tracks enable focused exploration of specific research domains, while their open and solution-agnostic design encourages the development of versatile systems capable of operating across multiple tracks. A tiered progression with gradually increasing complexity supports both novice and experienced teams, enabling a natural evolution of system capabilities without compromising scientific depth or spectator appeal.

2.2 Short-Term Vision

To ensure a smooth transition from the established leagues to the new SML format, the *EAI-WS* preserves essential skill requirements and explicitly welcomes most robot systems currently used in RoboCup@Work and RCLL. This allows teams to build upon existing hardware and software solutions while incrementally adapting them to the new manufacturing scenarios.

The workshop tracks are designed to expose teams early to integrated manufacturing workflows without requiring fully mature systems from the outset. This approach supports continuous learning and experimentation in increasingly complex environments, while lowering entry barriers for new participants.

For the 2026 season, selected objects and task elements from the RoboCup@Work Co-Worker challenge and the RCLL main track are retained. Reusing familiar objects across beginner and advanced tiers allows teams to focus on higher-level action logic, coordination, and planning aspects, rather than immediately addressing new perception or manipulation challenges. This staged introduction is intended to facilitate a gradual transition toward the full scope of the *EAI-WS* vision.

[1] The dynamic nature of task execution is intentionally reminiscent of cooperative planning scenarios found in popular games such as *Overcooked*, where simple physical actions combined with varying orders give rise to complex coordination and optimization challenges.

3 Task Description

The *EAI-WS* envisions a smart (toy) factory in which product orders and returns are processed autonomously on-demand. Robotic systems are required to produce, assemble, transport, and recycle products dynamically, reflecting key challenges of modern manufacturing environments.

To enable broad participation while supporting generalization to real industrial scenarios, the *EAI-WS* initially employs small modular polymer building blocks (e.g. LEGO Duplo™) as abstract representations of production and recycling components. This abstraction provides a flexible, safe, and affordable experimental environment, allowing teams to deploy compact robotic systems while preserving a nearly unlimited variety of product configurations. Product designs may range from simple objects to multi-component assemblies and may be unknown to teams prior to execution. The initial object set is shown in Fig. 2 and is intended to establish a common baseline for developing core robotic skills. Future iterations will gradually introduce more realistic industrial elements (e.g. wheels, axes) and advanced assembly steps requiring tools (e.g. screwdrivers), based on feedback from teams and insights gained during on-site events.

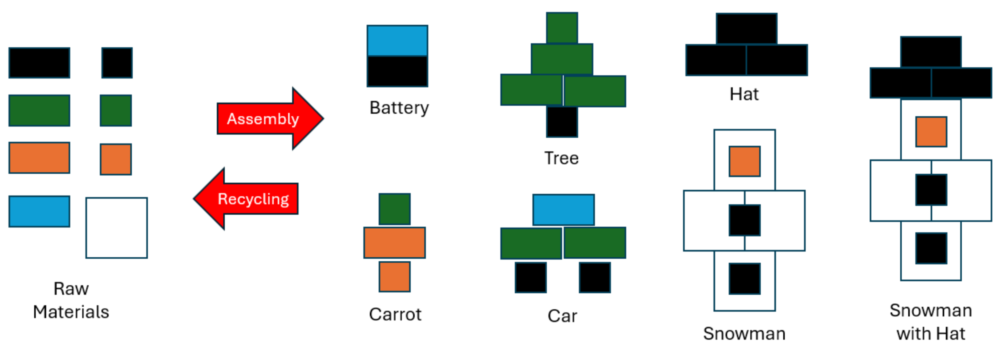

Figure 2: Initial set of raw materials and objects used for assembly and recycling tasks in the EAI-WS. The object set may evolve in future seasons according to feedback from teams and lessons learned during workshop events. Detailed part specifications are provided in the technical regulations.

The primary task objective is the autonomous handling of dynamic manufacturing workflows, including action planning, reliable transportation, and robust object manipulation under realistic constraints. The competition explicitly targets research challenges such as precise object perception, safe navigation in shared environments, resilient handling of components, and optimization of task execution.

As order complexity and workload increase, teams may explore different strategies to improve overall system performance, ranging from highly capable single robotic systems to coordinated multi-agent solutions. The league intentionally avoids prescribing a specific architectural approach, allowing teams to investigate how efficiency, robustness, and scalability can be achieved through different system designs.

To accommodate diverse robotic platforms, the workspace is standardized across two operating categories: ground-based platforms and humanoid-scale systems. Both categories share a common set of interaction elements, differing primarily in operating height, while otherwise permitting flexible implementations for single- and multi-agent configurations (see Fig. 3).

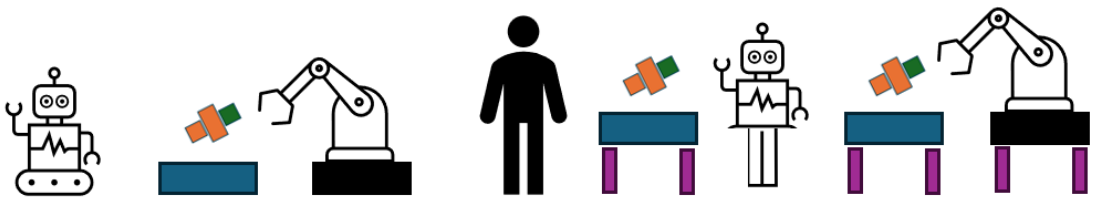

Figure 3: Standardized interaction elements at ground and human operating levels. Elevation platforms enable static manipulators to interact with shared workspaces, supporting collaboration across heterogeneous system designs.

In addition to fully autonomous operation, the *EAI-WS* provides a framework to explore human–robot interaction (HRI) and collaboration as relevant research dimensions. These aspects allow teams to investigate shared workspaces, cooperative task execution, and cross-team or cross-vendor integration under controlled and reproducible conditions.

4 Tracks

The tasks of the *EAI-WS* require robotic systems to combine physical execution with high-level decision-making, posing significant challenges for students and researchers at all stages. To structure this complexity and enable focused exploration of different research domains, the *EAI-WS* organizes on-demand manufacturing into three complementary tracks: *warehouse*, *workbench*, and *planning*. Each track targets a core capability relevant to modern production environments, while their combination represents integrated and cognitively capable robotic systems.

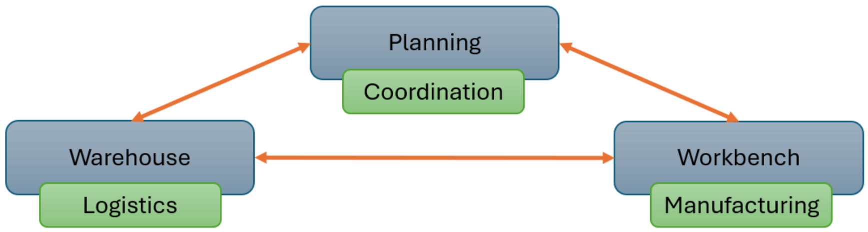

Figure 4: Overview of the three complementary SML tracks: warehouse, workbench, and planning. Together, they span physical execution, manipulation, and high-level coordination capabilities in smart manufacturing scenarios.

The separation into tracks follows three main intentions. First, teams can continue to focus on familiar research domains (e.g. logistics, manipulation, or planning) while gradually expanding their scope toward more integrated systems. Second, performance in fundamentally different domains can be evaluated independently, without abandoning the overarching objective of end-to-end autonomous operation. Third, the track structure explicitly enables human–robot interaction (HRI), inter-team collaboration, and partnerships across heterogeneous robotic systems, allowing teams to combine complementary expertise and explore cooperative strategies within a shared manufacturing scenario.

4.1 Warehouse – Reliable Transportation and Mobile Interaction

The warehouse track addresses transportation and mobile manipulation tasks that are fundamental to production logistics. Robotic systems are required to operate in a physical environment, navigate shared workspaces, locate objects on storage shelves, and transport raw materials or finished products between stations and customers.

The focus lies on reliable physical interaction, including safe navigation, object handling, and coordination with other agents. Teams are free to design their systems according to their research goals, ranging from single mobile robots to heterogeneous collections of platforms such as wheeled robots, humanoids, or hybrid systems.

4.1.1 Long-Term Vision

In the long term, the warehouse track aims to advance robust and flexible robotic systems capable of operating across diverse production environments. This includes challenges such as advanced manipulation during transport, container handling, environment inspection, and safe operation in human-populated spaces.

As workloads and scenario complexity increase, teams may explore strategies for cooperation between multiple robotic agents or integration with other tracks to improve overall throughput and resilience.

Future challenges may introduce additional sources of uncertainty, such as dynamic obstacles, reconfigurable storage layouts, or tasks requiring active environment modification (e.g. opening doors or reorganizing shelves), thereby fostering higher-level reasoning and problem-solving capabilities.

4.1.2 Short-Term Vision

In the short term, the warehouse track builds upon concepts established in the former leagues and prepares teams for reacting to dynamic events such as incoming orders or completed assembly steps. Existing solutions for navigation, manipulation, and task execution remain largely applicable, allowing established teams to transition smoothly while gradually adapting to more integrated manufacturing workflows.

4.2 Workbench – Manipulation and Assembly Execution

The workbench track focuses on advanced object manipulation and the execution of assembly and disassembly sequences required to produce or recycle requested products. It introduces a dedicated research space for precise handling of complex object configurations and multi-step building processes.

Teams may employ stationary robotic setups, such as table-mounted manipulators or multi-arm systems, as well as alternative concepts resembling small-scale production lines. To encourage mobile and integrated manufacturing approaches, robots participating in the warehouse track may also perform assembly tasks when technically feasible, either at workbench stations or on-board, without making such capabilities mandatory.

4.2.1 Long-Term Vision

The long-term objective of the workbench track is to approach industrially relevant manipulation challenges while maintaining flexibility and integration with other system components. This includes interaction with humans or other machines, coordination across multiple agents, and incorporation of manipulation capabilities into larger robotic systems.

Future extensions may involve deformable objects, image-based product specifications for previously unknown designs, and mandatory tool usage (e.g. screwdrivers or drilling operations). To support integration with planning and warehouse systems, robots will be required to communicate expected processing times and material requirements for given assembly tasks.

4.2.2 Short-Term Vision

The short-term vision introduces manipulation challenges gradually, enabling teams to build reliable execution pipelines before tackling complex assemblies. Simple components and actions, such as stacking modular building blocks, support incremental skill development and facilitate collaboration between different agents, including humans.

Allowing stationary workbench setups and inter-team collaboration lowers entry barriers for new participants and enables teams to contribute to the *EAI-WS* without prior expertise in warehouse logistics.

4.3 Planning – Strategy Formulation and Coordination

The planning track addresses high-level coordination, material flow optimization, and execution monitoring across warehouse and workbench operations. Given the diversity of robotic hardware and capabilities, planning systems must adapt dynamically to changing tasks, environments, and team configurations.

To enable meaningful comparison of planning approaches, a lightweight two-dimensional simulation environment supports standardized planning scenarios, such as single general-purpose agents, small fleets of specialized robots, or larger heterogeneous systems. Unified agent models with configurable capabilities (e.g. speed, payload, or skill sets) allow evaluation of planning strategies in terms of computational effort, predicted execution time, and overall efficiency, independent of specific hardware implementations.

Planning solutions are ultimately expected to interface with real robotic systems. Teams may generate plans for their own robots, for collaborating teams, or for human operators. Plan quality can then be assessed based on prediction accuracy, robustness to execution failures, and the ability to adapt through re-planning.

4.3.1 Long-Term Vision

In the long term, the planning track aims to enable factory-wide coordination across heterogeneous fleets composed of self-built and external robotic systems. Standardized interfaces allow planning teams to assign high-level tasks without direct control over low-level execution, focusing research on resource contention, capability-aware planning, and decision-making over extended horizons.

Online feedback from physical execution supports rapid re-planning in response to errors or unexpected events, promoting reliable and efficient production and recycling under real-world constraints.

4.3.2 Short-Term Vision

Initially, evaluation of the planning track may be limited until a common simulation environment and interfaces are fully established. Teams with existing planning systems may continue to apply their approaches implicitly by achieving higher task completion rates in physical runs, similar to previous league concepts.

As collaboration across teams and tracks becomes increasingly relevant, a short-term objective is to jointly develop standardized interfaces and shared simulation tools within the SML community, providing a foundation for systematic planning evaluation in future seasons.

5 Human- and Multi-Robot Interaction

Teams may choose to participate in all or only selected tracks, performing some or all required tasks, and are free to design their robotic systems according to their research focus and available resources (see Section 6). To ensure broad accessibility while maintaining an end-to-end manufacturing scenario, the *EAI-WS* provides multiple mechanisms to compensate for missing capabilities in individual tracks: human collaboration and inter-team partnerships.

5.1 Human–Robot Collaboration

Teams are permitted to perform the tasks of one or more tracks with the assistance of a human co-worker, such as a team member. Depending on the skipped tracks or tasks, this may include manually retrieving raw materials from storage, performing assembly or disassembly steps at a workbench, or reorganizing task sequences.

For the planning track, teams may rely on a predefined, non-optimized baseline execution order or manually adjust task sequences within a limited preparation time. These options allow teams to focus their research and development efforts on selected capabilities while still participating in integrated manufacturing runs.

Beyond their practical role, these mechanisms explicitly encourage human–robot interaction and enable direct comparison between human-driven and autonomous solutions, supporting the exploration of hybrid production workflows (see Section 6.7).

5.2 Team Partnerships

As an alternative to human collaboration, teams may form partnerships with other teams specializing in complementary tracks. For example, a team focusing on warehouse logistics may collaborate with another team providing assembly or planning capabilities.

In such partnerships, robots interact directly with external systems to complete shared tasks, enabling higher degrees of autonomy without requiring each team to cover all tracks independently. To reflect the shared risk and coordination effort, rewards for successfully completed tasks are distributed across all participating partners (see scoring in Section 8).

5.3 Multi-Robot Collaboration

The long-term vision of the SML is a smart factory environment in which robotic systems from multiple teams and vendors operate concurrently within a shared workspace. This setting fosters cross-team collaboration, diverse forms of human–robot and robot–robot interaction, and increasing levels of autonomy and efficiency at system level.

While human collaboration and team partnerships primarily support adaptation and skill development during early stages of participation, robot–robot collaboration remains central even for highly capable systems. This is reflected in the tier structure, where the expert tier envisions multiple teams operating simultaneously in a shared environment without spatial separation.

Earlier tiers are designed to support gradual development of robustness, coordination, and interaction skills, allowing teams to progressively prepare for complex, densely populated factory scenarios involving larger heterogeneous fleets (see Section 7).

6 Technical Regulations

The technical regulations of the *EAI-WS* are intentionally minimal and primarily serve to ensure safety, comparability, and practical feasibility during onsite events. They are not intended to prescribe specific robotic designs or system architectures. Instead, they define a small set of boundary conditions within which teams are encouraged to explore diverse and innovative solutions.

Teams may participate with any robotic system or fleet configuration, provided it can autonomously perform tasks in at least one track. Robots may be reused across multiple tracks if applicable, allowing both single, highly capable systems and heterogeneous fleets of specialized robots. This flexibility is a core design principle of the *EAI-WS* and reflects the exploratory nature of the workshop format in 2026.

6.1 Objects and Materials

Industrial production involves a wide variety of components differing in size, weight, material, and assembly complexity. Directly replicating such diversity would require specialized and costly hardware, limiting accessibility for student teams.

To balance affordability and expressive task complexity, the *EAI-WS* employs standardized, lightweight building blocks such as LEGO Duplo™ elements or equivalent 3D-printed replicas [2]. These components allow teams to investigate manipulation, assembly, planning, and logistics challenges while using low-cost actuators and sensors.

The initial object set consists of two block types (2×2×2 and 4×2×2) in five different colors. This set enables the construction of a wide range of products while providing a stable foundation for early competitions. Future iterations may introduce additional shapes, materials, colors, or tools to gradually increase task complexity and realism.

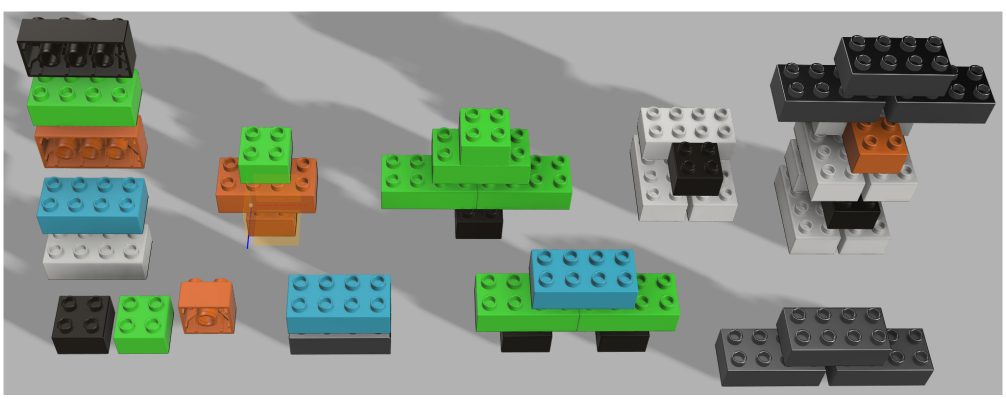

Figure 5: CAD Renderings of selected target materials and products from the *EAI-WS*

6.2 Warehouse Robots

Warehouse robots are intended to perform transportation and manipulation tasks across the production floor. Teams may deploy any type of mobile robotic platform, ranging from small ground-based systems to humanoid robots, provided they can safely navigate the environment and interact with objects, humans, and other robots.

Typical tasks include locating items on storage shelves, picking and transporting components or products, and delivering them to target stations. Payload capacity is not explicitly restricted at concept level, allowing teams to explore different inventory and batching strategies. This does not imply that higher payloads are inherently advantageous, but preserves openness for alternative efficiency concepts.

Advanced systems may combine logistics with auxiliary tasks such as inspection or maintenance, and may dynamically adapt their role depending on system capabilities and task demands.

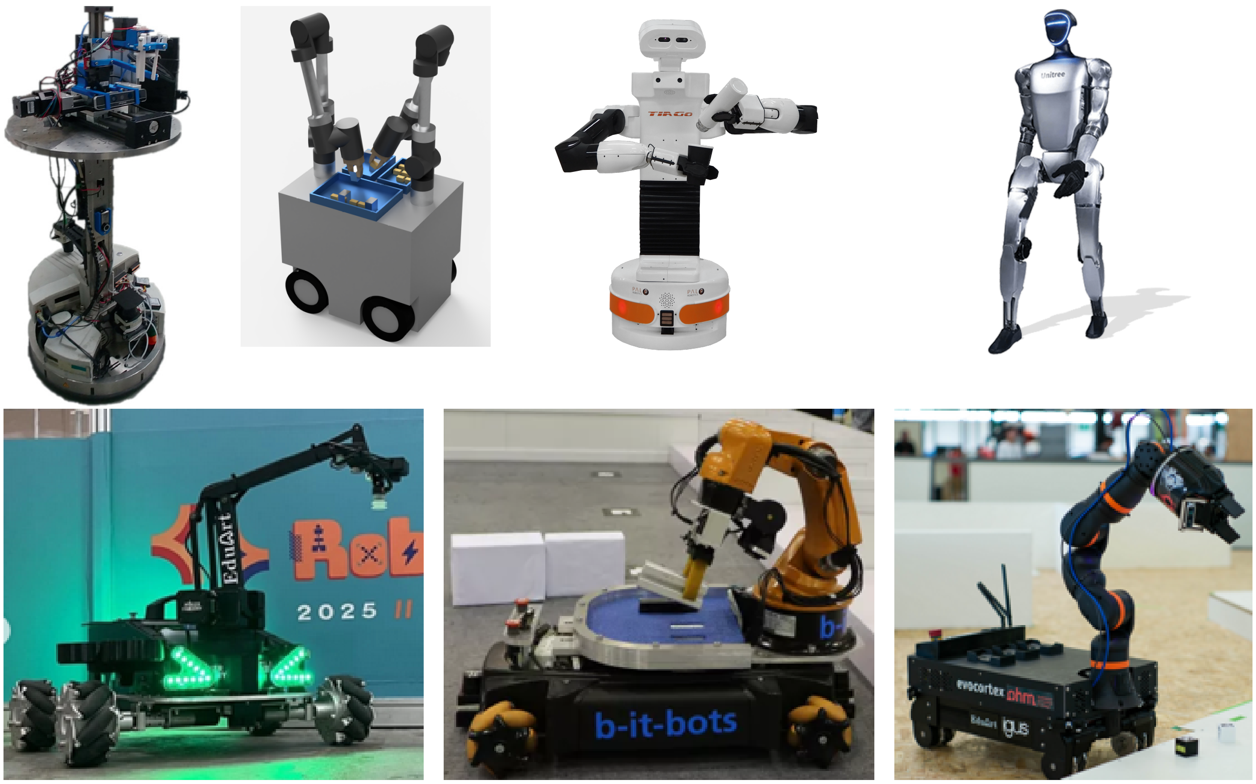

Figure 6: Representative examples of mobile warehouse robots that may participate in the SML, ranging from small ground-based platforms to humanoid systems. Teams are free to choose their system composition.

6.3 Workbench Robots

The workbench track focuses on advanced object manipulation and execution of assembly and disassembly sequences. Rather than prescribing a specific form factor, the track emphasizes the capability to reliably perform structured manipulation tasks involving multiple components.

Teams may deploy dedicated stationary assembly systems positioned at workbench stations, for example using one or more robotic manipulators mounted on a stable base. Alternatively, mobile robots participating in the warehouse track may perform assembly tasks themselves, either at workbench stations or on-board, provided they meet the task requirements. This explicitly encourages the development of versatile systems without making such designs mandatory.

Where stationary workbench systems are used, they must be mountable either directly on the floor or on an elevation structure that lifts the operating surface to human working height. This ensures compatibility with both ground-level mobile robots and systems operating at human height, enabling seamless collaboration across different robot classes.

Workbench systems may integrate arbitrary sensor modalities and specialized tooling where appropriate. Safety and stability requirements apply to all setups, regardless of whether assembly is performed by stationary or mobile platforms. Where stationary systems are used, control and decision-making must be performed autonomously by an embedded computing unit.

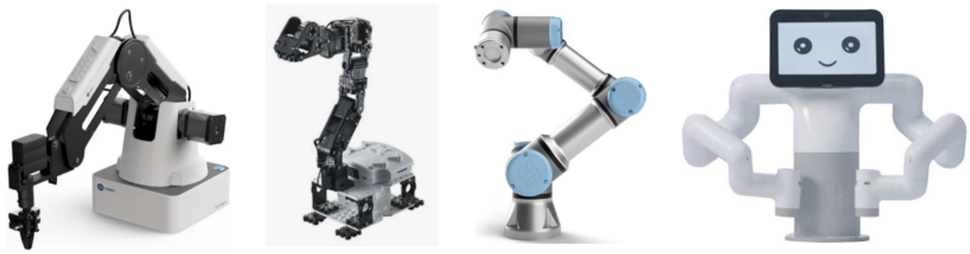

Figure 7: Example manipulator and workbench setups suitable for assembly and disassembly tasks. Stationary systems may be mounted at ground or human operating height.

6.4 Robot Specifications

A limited set of mandatory design constraints is defined in Tab. 1 to ensure participant safety, logistical feasibility, and fair comparison of different approaches. These constraints are designed to accommodate most existing RoboCup Industrial systems while remaining open to emerging platforms such as humanoid robots.

Table 1: System Requirements for Mobile Robots and Workbench Stations

<table>
<tr><th>Requirement</th><th>Mobile Warehouse Robot</th><th>Workbench Station</th></tr>
<tr><td>Maximum Number</td><td>3 mobile robots</td><td>2 workbench stations</td></tr>
<tr><td>Power Supply</td><td>Battery powered; no exhausts or emissions</td><td>Main power (110 - 230 V AC) or battery powered</td></tr>
<tr><td>Emergency Stop</td><td colspan="2">Reachable safety stop disabling all actuators</td></tr>
<tr><td>Design Safety</td><td colspan="2">No sharp edges, exposed wiring, uncovered gears, hot surfaces, or other hazards</td></tr>
<tr><td>Maximum Weight</td><td>100 kg</td><td>60 kg</td></tr>
<tr><td>Maximum Dimensions</td><td>80 cm × 60 cm × 150 cm</td><td>80 cm × 60 cm × 100 cm (190 cm incl. elevation)</td></tr>
<tr><td>Maximum Speed</td><td>1.5 m/s</td><td>1.5 m/s</td></tr>
<tr><td>Robotic Arms</td><td>Up to 2 arms</td><td>Up to 4 arms</td></tr>
<tr><td>Mobility / Mounting</td><td>Navigation on flat ground</td><td>Must be mountable on elevation structures</td></tr>
</table>

6.5 Planning Servers

Planning functionality may be implemented in a decentralized manner on individual robots or via a central planning server. Centralized planning servers must be locally hosted (e.g., laptop or desktop PC); cloud-based computation is not permitted.

Communication between robots and planning systems must use the official SML network infrastructure. While standardized interfaces are encouraged to facilitate cross-team collaboration, they are not mandatory during initial competitions to allow reuse of existing software stacks.

Simulation environments may be used to evaluate planning strategies under standardized conditions. However, plans are ultimately intended to be executed by physical agents, and planning quality may be assessed based on execution robustness and error handling in real-world scenarios.

6.6 Arena Elements

The arena consists primarily of standardized storage shelves and solid white walls [3][4]. By using commonly available shelving systems (40 cm × 90 cm × 90 cm) [5], competition setups can be reproduced globally without specialized equipment.

Shelves provide two operating heights: ground level for small to mid-scale mobile robots, and human operating height for humanoid or elevated systems. Workbench stations must be mountable either directly on the floor or on elevation structures to align with these operating heights.

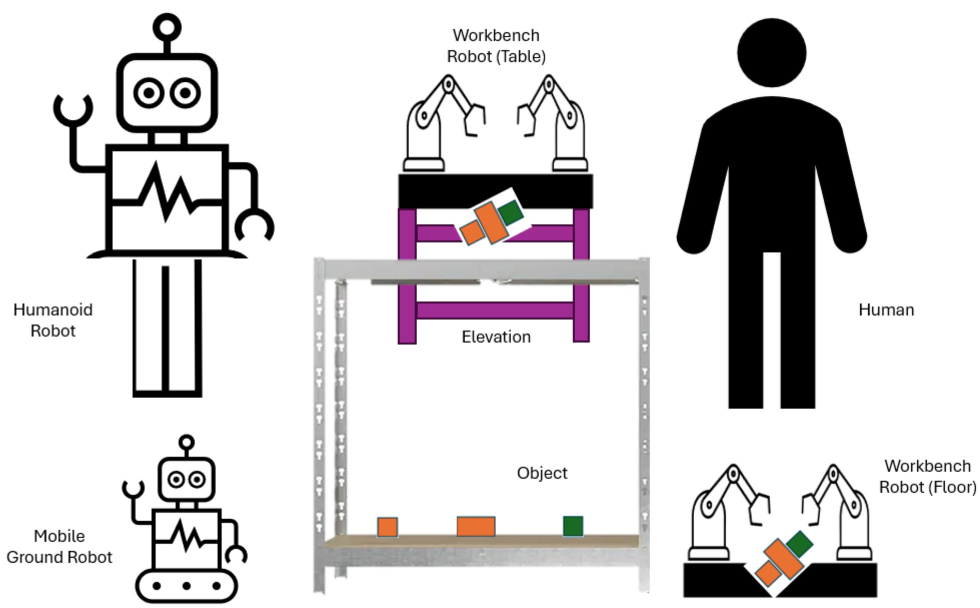

Figure 8: Standardized storage shelf with two operating heights: ground level for wheeled robots and human operating height for humanoid or elevated systems. Workbench stations may be mounted accordingly.

Grey Euro-boxes (30 cm × 40 cm × 12 cm) [6] may be placed on storage shelves and workbench stations to serve as optional storage and buffering elements. Containers may hold either individual components or batches of raw materials, depending on the chosen team strategy.

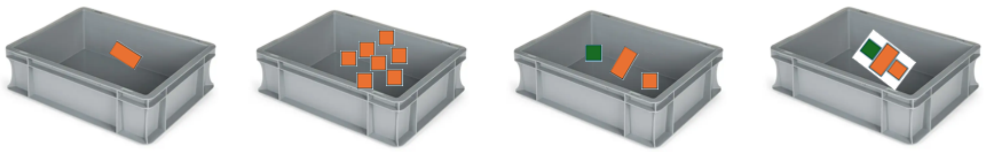

Figure 9: Euro-boxes as optional storage and buffering elements. Containers may hold single components or batches of materials, depending on team strategies.

Robots are permitted to transport complete containers if their system design supports it. However, container handling is considered an optional interaction artifact rather than a defining task primitive. Teams are encouraged to prioritize flexible single-object handling and internal inventories where appropriate, in order to avoid monopolizing shared resources and to enable interaction with heterogeneous agents.

6.7 Arena Layout

The standard *EAI-WS* arena consists of two mirrored sides (A and B), each containing a warehouse section and a workbench section. The sides may be physically separated or connected via a central area, enabling either independent benchmarking or shared-space operation.

This design supports direct comparison of different system architectures as well as complex planning scenarios involving multiple teams operating concurrently in a shared environment.

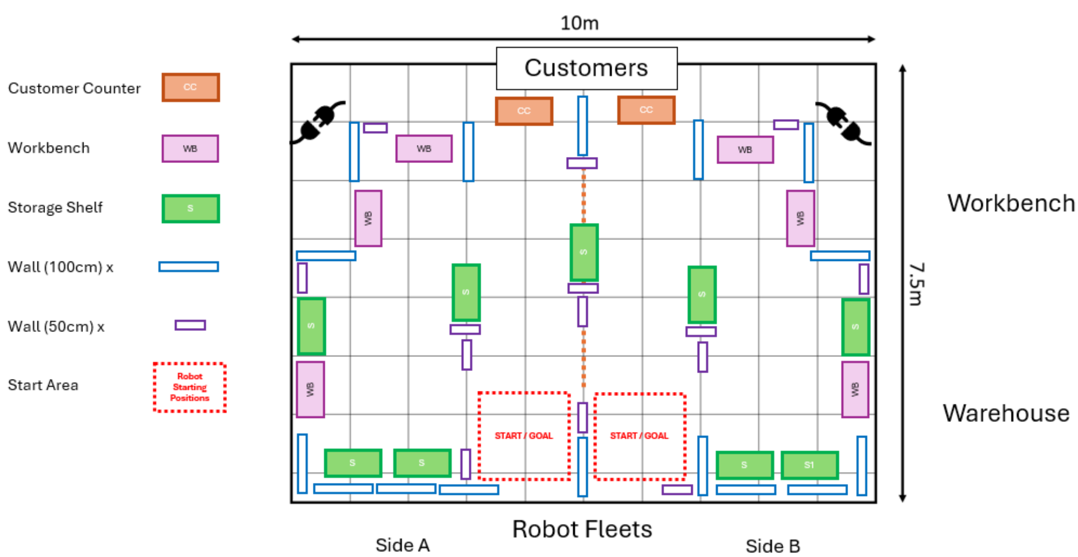

Figure 10: Exemplary arena layout showing mirrored environments for independent benchmarking and optional shared-space operation for advanced tiers.

6.8 Levels

Arena complexity and active elements are adapted per competition tier (see Section 7). Earlier tiers may restrict workspace sharing or deactivate certain stations, while advanced tiers gradually introduce higher density, resource contention, and inter-team interaction.

6.9 Infrastructure

Power supply, networking, and monitoring infrastructure must be arranged outside the arena to ensure safe operation and unobstructed robot motion. Cables must not cross active robot areas and should be routed along arena boundaries.

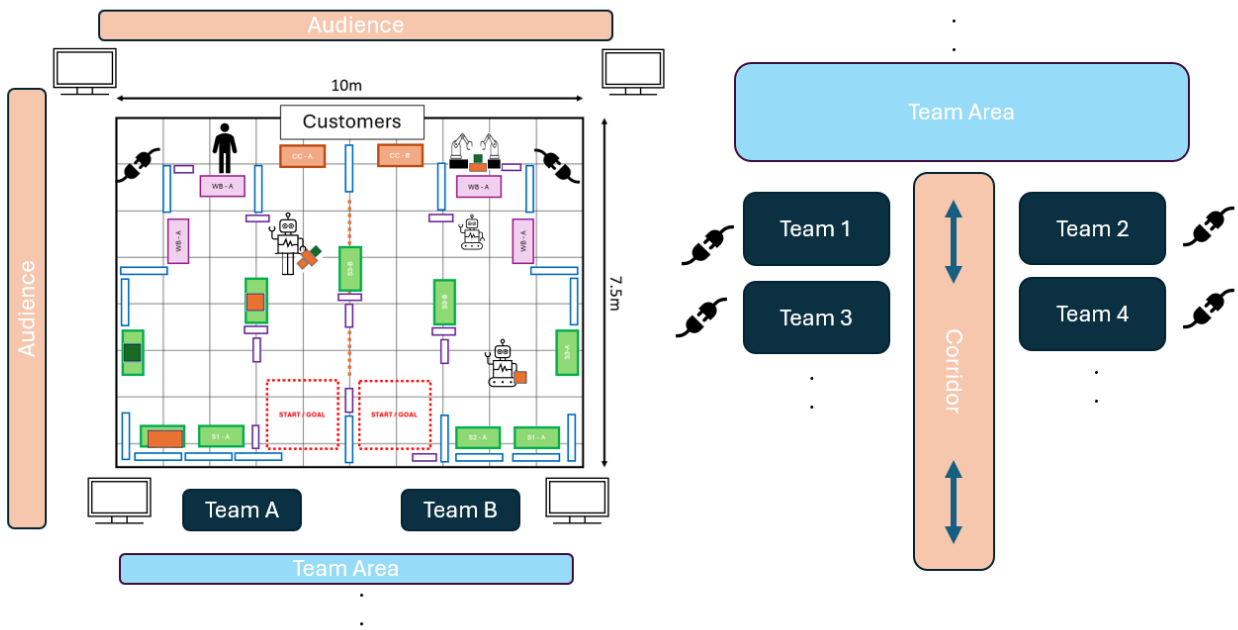

Figure 11: Exemplary infrastructure and team space layout for an onsite SML event. Power supply, networking, and monitoring infrastructure are placed outside the active arena. A central corridor allows safe transport of robots between team areas and the competition space. Monitors may display task descriptions and selected robot state information for participants and visitors.

Monitors may be placed at arena corners to display task descriptions, robot state information, or visualizations of internal planning and perception processes. A central corridor must remain unobstructed to allow teams and robots to move safely between workspaces and the arena. Robot speed in this corridor is strictly limited to 0.4 m/s.

7 Competition Design

The *EAI-WS* competition is structured into multiple benchmark tests organized across three main tiers: *Beginner*, *Advanced*, and *Expert*. The tiered design establishes a low entry barrier for new teams while progressively increasing task complexity to challenge advanced researchers and mature robotic systems. This structure allows participation from a broad audience, ranging from undergraduate students to experienced research groups.

Each tier is further subdivided into three *stages* representing different aspects of the manufacturing process: *Production*, *Recycling*, and *Life-Cycle*. While the general structure is fixed, specific parameters (e.g., number of orders, execution time, or active stations) may be adapted at real events to balance feasibility, fairness, and task difficulty based on team feedback and league maturity.

7.1 Tier & Stage Overview

7.1.1 Beginner Tier

The Beginner tier serves as an entry point to the league and focuses on validating fundamental autonomous capabilities of a single team or robot fleet. Teams demonstrate reliable execution of production, recycling, and basic life-cycle tasks under controlled conditions. Physical separation between arena sides ensures undisturbed execution and allows for direct comparison between different approaches. This tier is designed to lower entry barriers for new teams while preparing them conceptually and technically for more complex scenarios.

7.1.2 Advanced Tier

The Advanced tier increases task complexity by introducing higher workloads, resource contention, and optional pre-assembly steps. While single-robot systems may still participate, fleet-based solutions are increasingly rewarded as coordination, batching, and scheduling become relevant. Arena sides remain separated, enabling teams to analyze their own performance under stress and allowing spectators to compare different system designs under identical conditions. This tier bridges basic autonomy and large-scale coordination challenges.

7.1.3 Expert Tier

The Expert tier represents a shared factory environment without physical separation, operating continuously over extended periods. Multiple teams and heterogeneous systems coexist and collaborate within the same workspace. Execution becomes visually dense and less structured, reflecting realistic factory dynamics at scale. Successful operation requires advanced coordination, robust fleet management, and inter-system negotiation, making this tier a benchmark for large-scale autonomous production and logistics systems.

7.2 Task Complexity

Table 2 summarizes the intended task complexity, material usage, and environment configuration for each tier and stage. All numerical values represent typical target ranges and may be adjusted for individual events depending on product design, arena layout, and team experience.

Lifecycle stages combine production and recycling tasks and introduce shared raw materials between new orders and returned products, increasing planning complexity and resource contention.

Tier	Stage	Time	Orders	Returns	Raw Mat.	Products	Arena	Fleet Size
Beginner	Production	5 min	2	0	5 ± 1	2 ± 0	A / B	1 - 3
	Recycling	5 min	0	2	5 ± 1	2 ± 0	A / B	1 - 3
	Lifecycle	10 min	3	2	10 ± 3	5 ± 1	A / B	1 - 3
Advanced	Production	10 min	5	0	10 ± 3	5 ± 1	A / B	1 - 6
	Recycling	10 min	0	5	10 ± 3	5 ± 1	A / B	1 - 6
	Lifecycle	15 min	5	5	20 ± 8	10 ± 2	A / B	1 - 6
Expert	Production	20 min	20	0	40 ± 15	20 ± 5	A + B	3 - 12
	Recycling	20 min	0	20	40 ± 15	20 ± 5	A + B	3 - 12
	Lifecycle	30 min	30	20	100 ± 30	50 ± 10	A + B	3 - 12

Table 2: Overview of task complexity across tiers and stages. Ranges indicate adjustable parameters depending on product design and league maturity. Lifecycle stages introduce shared raw materials between new orders and recycled products.

7.3 Junior Tier

The Junior tier adapts the competition concept for younger participants and outreach activities. Task complexity is significantly reduced, and partially or fully remote-controlled robots may be allowed. This tier introduces fundamental robotics concepts such as hardware design, control, and human–robot interaction in a playful and accessible manner.

Conceptually, the Junior tier resembles cooperative task-solving scenarios with dynamic orders and physical interaction, serving as an educational entry point rather than a competitive benchmark.

8 Scoring

All participating teams are evaluated using a unified, percentage-based scoring system. The scoring framework is designed to reflect two core principles of the *EAI-WS*: (i) the degree of autonomous system capability across the three tracks, and (ii) the ability of a system to successfully complete production and recycling tasks end-to-end.

Each track (warehouse, workbench, planning) contributes an individual performance score in the range of 0% to 100%. Teams gain percentage points by successfully completing track-specific actions using autonomous robotic systems, such as navigation, object handling, assembly steps, or plan generation and execution. Non-participation in a track results in a score of 0% for that track.

In addition to track-specific scores, teams are evaluated on their task completion rate, defined as the percentage of successfully completed product and return orders within a given stage. This metric captures the overall effectiveness of the system under realistic workload constraints.

The total stage score of a team is computed as the *median* of all individual track scores and the task completion rate. Using the median instead of a sum prevents single-track dominance and emphasizes balanced system autonomy and completeness. If track difficulty is perceived as unbalanced for a specific event or tier, optional weighting factors may be introduced to moderately increase or decrease the influence of individual track scores. Such adaptations are considered part of the event-specific regulations and may evolve based on experience gained during initial competitions, especially for the expert tier.

Table 3 illustrates an example scoring outcome for a beginner-tier production stage. Four teams participate with different system configurations, ranging from single-track autonomous solutions to multi-track systems and collaborative setups involving other teams. The example demonstrates the intended scoring philosophy: higher autonomy across multiple tracks is rewarded, while teams using human–robot interaction or partnerships can still participate in the full benchmark and receive meaningful evaluations.

Team	**Mode**	**Warehouse**	**Workbench**	**Planning**	**Orders**	**Total (Median)**
A	(W)	80%	0%	0%	100%	45%
B	(W+WB)	75%	60%	0%	50%	46.25%
C	(W+P, coll.)	90%	0%	$0.5 \cdot 85\%$	80%	53.125%
D	(W+WB+P)	85%	70%	65%	40%	65%

Table 3: Example participation and scoring across the three tracks. W = Warehouse, WB = Workbench, P = Planning. Non-participation in a track results in a score of 0% for that track. Team collaborations are rewarded with 50% of the partner track performance. The total score is computed as the median of all track scores and the task completion rate, reflecting overall system autonomy and completeness.

8.1 Scoring Points

Percentage points are awarded for successfully completing track-specific requirements appropriate to the current tier. These include, but are not limited to, reliable navigation, correct object handling, successful assembly or disassembly steps, accurate plan generation, and completion of assigned orders.

For collaborative setups, such as inter-team partnerships, each participating team receives a fraction of the partner's performance score for the shared track. By default, this fraction is set to 50%, reflecting shared responsibility while still incentivizing full autonomous solutions.

Table 4 provides an indicative overview of potential scoring criteria. The exact metrics and thresholds are expected to be refined in future rulebooks or defined locally for individual events. Depending on event preferences, track scores may either be computed against predefined performance targets (e.g., completion of all required actions) or normalized relative to the best-performing team in a track, which then defines the 100% benchmark. Both approaches are compatible with the proposed scoring philosophy and may be selected per event.

Table 4: Indicative Overview of Scoring Criteria

Category	**Criteria**
General	Task completion rate, execution time efficiency, robustness
Warehouse	Reaching target locations, picking correct objects, delivering correct objects
Workbench	Correct (dis-)assembly steps, object handling precision, completed products
Planning	Plan computation time, execution time prediction accuracy, action ordering quality

8.2 Penalties

Teams may be penalized for errors that negatively impact task fulfillment, safety, or system robustness. Severe safety-related violations, such as collisions, may terminate a run, while operational errors may be accumulated and reflected in the final score.

Examples include, but are not limited to:

- Dropping or damaging objects
- Causing collisions
- Logistic errors (e.g., transporting incorrect items)
- Assembly errors (incorrect or incomplete products)
- Order errors (missed or incomplete deliveries)

8.3 Winning a Track, Tier, and the Workshop

For each tier, winners are determined in four categories: one overall tier champion and three best-in-track awards (warehouse, workbench, planning). This structure rewards both general-purpose autonomous systems and outstanding specialization in individual research domains.

The overall workshop winner is determined by aggregating the total median scores achieved across all tiers. Optional complexity factors may be applied to later tiers to better reflect increasing task difficulty and system maturity.

Similarly, cumulative track scores across all tiers determine the best-in-track winners, highlighting sustained excellence in specific capabilities throughout the competition.

9 Event Structure

The event structure defines how competition runs are organized and executed during onsite events. It specifies the interaction between teams, robots, referees, and the arena, while intentionally remaining flexible to accommodate different event formats, time constraints, and participation levels. The described structure represents a reference framework and may be adapted for individual events, especially during the early years of the league.

9.1 Participation Declaration

Prior to each stage, teams must declare their intended participation for the available tracks (warehouse, workbench, planning). Teams may also announce the use of human–robot interaction or inter-team partnerships as defined in Section 6. This declaration allows referees to configure the arena, scoring, and evaluation accordingly.

Changes to participation modes between stages are permitted, enabling teams to incrementally increase autonomy or explore different collaboration strategies across the competition.

9.2 Arena Usage and Team Grouping

In the beginner and advanced tiers, the arena is typically divided into two physically separated environments (Side A and Side B). Two teams or team groups may operate simultaneously under identical conditions, enabling direct performance comparison while ensuring undisturbed execution.

In the expert tier, the full arena (A+B) is opened as a shared factory floor. Multiple teams and heterogeneous systems operate concurrently within the same environment, requiring coordination, negotiation, and robust interaction strategies. Team grouping and order of participation may be randomized to ensure diverse benchmarks across different system combinations.

9.3 Preparation and Execution Phases

Each run is divided into a preparation phase and an execution phase.

During the preparation phase, teams install their robots in the arena, perform system startup procedures, and initialize software components. Typical preparation activities include booting systems, checking sensors and actuators, and verifying communication links. Preparation phases are time-limited to ensure smooth event flow, with recommended durations of approximately 5 minutes per run.

The execution phase begins once the arena and task configuration are finalized. Robots must operate fully autonomously during execution, except where human–robot interaction or team partnerships have been explicitly declared. The execution phase ends when the predefined time limit for the stage is reached (see Section 7) or when all tasks have been completed.

Teams may restart systems during execution if required, but such interventions may incur scoring penalties. Once execution concludes, teams must safely stop their robots and remove them from the arena to allow setup for subsequent runs.

9.4 Visualization and Audience Interaction

To enhance transparency and spectator understanding, task descriptions, order lists, and selected robot state information may be visualized during events. This may include planned action sequences, simplified simulation replays, localization data, or abstracted perception outputs.

Planning-related computations may be performed during preparation phases and visualized using lightweight simulation tools. Displaying predicted execution strategies alongside real robot behavior enables judges and audiences to better assess planning quality, robustness, and deviations caused by real-world execution.

9.5 Refereeing and Arena Reset

After each run, referees reset the arena to a defined initial state. This includes restoring object positions, refilling storage shelves, and verifying the safety of the environment. Arena reset procedures are standardized to ensure fair and reproducible benchmarking across teams and runs.

Referees may interrupt runs in the case of safety violations or severe malfunctions. Such interventions are documented and reflected in the scoring according to the penalties defined in Section 8.

9.6 Multi-Day Event Structure

RoboCup events typically span multiple setup and competition days. The *EAI-WS* is designed to leverage this structure by separating system integration, learning-oriented trial runs, and official benchmark evaluations. This enables teams to iterate on their systems, recover from failures, and demonstrate robust autonomy without relying on single-shot performances.

	Day 1	**Day 2**	**Day 3**	**Day 4**	**Day 5**	EAI-WS
	Setup	Free Practice	Beginner	Advanced	Expert	Example Schedule
08:00						
10:00			Production	Production	Life-Cycle	
12:00	Arena Setup					
14:00			Recycling	Recycling		Open Arena
16:00						Competition
18:00	Briefing		Life-Cycle	Life-Cycle		Blocked
20:00						
22:00						

Figure 12: Example schedule for the *EAI-WS* during an onsite SML event. Open arena timeslots may be used for practice runs or other workshop contents. Event-specific schedules may be communicated onsite by the local committee.

9.7 Retry and Evaluation Philosophy

To encourage robust system development and reduce the risk of single-run failures, the *EAI-WS* allows multiple attempts per team and stage whenever time permits. Unless stated otherwise, only the best-performing run contributes to the official score. Additional runs serve learning, debugging, and demonstration purposes.

This approach balances scientific benchmarking with the realities of complex autonomous systems operating in real environments.

10 Technical Challenges

As part of the *EAI-WS*, a set of optional technical challenges is proposed to complement the core competition tracks. These challenges address relevant research problems that are not directly covered by the warehouse, workbench, or planning tracks. In contrast to the fixed league tracks, technical challenges are intentionally dynamic and non-permanent. They serve as exploratory benchmarks for novel ideas, emerging technologies, and experimental task formulations that may inform future track designs.

Technical challenges are non-mandatory and do not affect the main competition ranking. Instead, they provide teams with an opportunity to evaluate new concepts, demonstrate specialized capabilities, and collect feedback from the community in a low-risk setting. In addition, individual tracks may host annual challenges that focus on specific sub-problems, such as advanced tool usage, environment exploration, or perception under uncertainty.

The authors of this workshop concept explicitly encourage teams, researchers, and industrial partners to propose technical challenges. Community-driven contributions are considered a key element in keeping the league innovative, relevant, and scientifically grounded.

Potential challenge topics include, but are not limited to:

Industry-Sponsored Challenges Industrial partners of the RCSML are encouraged to contribute real-world R&D challenges derived from their production environments. Examples include interoperability tasks, system integration problems, or workflow optimization scenarios. Support for standards such as VDA5050 may facilitate the integration of industrial hardware and software components into these challenges.

Real-Product Assembly Challenges Assembly or disassembly tasks involving realistic products and components of varying materials and tolerances. Example scenarios include drivetrain assemblies consisting of gearboxes, shafts, and actuators, or similar modular industrial subsystems.

Anomaly Detection and Recovery Challenges Robots are required to detect, report, and potentially resolve unexpected situations, such as blocked passages, faulty or misplaced materials, unsorted storage locations, or malfunctioning tools. The focus lies on robustness, situational awareness, and autonomous decision-making under uncertainty.

11 The Role of Humanoids

With humanoid robots gaining increasing attention due to recent research progress and growing commercial availability, the *EAI-WS* explicitly supports and encourages their experimental use across all physical tracks. Humanoids represent a promising class of general-purpose systems, particularly for tasks involving manipulation at human operating height, tool usage, and interaction in shared environments.

At the same time, their practical advantages and competitiveness relative to established robotic system designs remain an open research question. For this reason, humanoids are *not mandatory* for participation in the *EAI-WS*. Instead, the league deliberately maintains hardware openness, allowing teams to evaluate humanoids alongside wheeled platforms, stationary workcells, and heterogeneous fleets under identical task conditions.

To support early exploration, optional incentives such as bonus points or dedicated demonstration opportunities may be introduced in early events. These incentives are intended to lower the risk for teams willing to experiment with humanoid platforms and to accelerate the collection of empirical insights regarding their strengths and limitations.

This approach aligns with the broader vision of the RoboCup Federation, which promotes humanoid participation across leagues while acknowledging that task-specific and specialized systems may currently outperform general-purpose designs. Consequently, the EAI-WS formulates its tasks independently of specific robot morphologies, allowing performance and robustness to emerge naturally from open competition rather than from predefined hardware assumptions.

12 Call for Participation

The RoboCup Smart Manufacturing League (SML) invites motivated students, researchers, and academic laboratories to participate in shaping a new industrial competition format. The league is designed as an open and evolving research environment that welcomes diverse robotic system designs, levels of expertise, and research focuses.

Participants are encouraged to contribute not only through competition runs, but also through technical discussions, demonstrations, and collaborative experiments during onsite events. In particular, the workshop-oriented structure of the initial SML editions aims to foster knowledge exchange, rapid prototyping, and constructive feedback across teams and disciplines.

To strengthen outreach and education, the SML emphasizes transparency and accessible task design. Modular products, clearly structured challenges, and intuitive visualization of plans and robot behavior are intended to make smart manufacturing concepts understandable to both participants and the general audience.

For questions, feedback, or expressions of interest, please contact the league via the official mailing list: robocup-sml@lists.robocup.org.

13 Acknowledgements

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We also thank additional contributors, reviewers, and collaborators who provided feedback, ideas, and critical discussion throughout the process, as well as industrial partners and associated research groups for sharing practical insights and constraints from real-world applications.

Any remaining design choices and interpretations are the responsibility of the authors. The workshop is intentionally designed to evolve based on on-site experience and participant feedback.

Some figures contain illustrative images collected from publicly available web sources. These images are used solely for explanatory purposes and do not represent original research results or prescribe specific hardware choices.

14 Upcoming Seasons – Letter to the Teams

We are aware that the structural changes introduced with the Smart Manufacturing League (SML) will require teams to adapt their robots and software stacks. As with any major transition, this may temporarily affect competitiveness, especially for established systems. At the same time, the vast majority of required core skills remain familiar to the RoboCup Industrial community: localization, navigation, manipulation, planning, and coordination and robust hardware control.

We therefore encourage teams to approach the upcoming seasons with confidence and curiosity. The SML is designed to evolve existing strengths into a new, exciting benchmark that bridges real-world industrial demands, current research objectives, and an engaging competition format. We are excited to shape this next chapter of RoboCup Industrial together with the community, advancing robotic research for Industry 5.0 and beyond.

To illustrate the core idea of the proposed *Embodied-Autonomous-Intelligence-Workshop (EAI-WS)* format, the cooperative game *Overcooked* serves as a useful analogy. In the *EAI-WS*, robotic agents take the role of the cooks: retrieving materials from storage, performing processing and assembly steps, and delivering finished products to customers. Recognizable products composed of clearly distinguishable raw materials allow task requirements and action sequences to become intuitive at a glance. This results in a competition format that is easy to understand for spectators, yet challenging to master, while retaining scientific depth across perception, manipulation, planning, and coordination.

By explicitly supporting both ground-level systems from RoboCup@Work and human-level platforms from the former RCLL, teams may continue to use their existing robots with limited hardware changes. In many cases, only software adaptations will be required. Elevation structures for static workbench setups enable collaboration across operating heights and encourage novel hardware concepts. Humanoid robots, while not yet mature enough to consistently outperform specialized systems, are included as an optional platform. This allows teams to explore their potential early and benchmark them against established solutions under identical task conditions.

One of the most visible technical changes is the introduction of colored polymer bricks as standardized target objects. This requires new perception pipelines for most teams; however, given recent advances in AI-based vision methods, this is considered a reasonable and future-oriented adaptation. We encourage the use of synthetic data generation, 6-DoF pose estimation networks, and publicly available CAD models, for example via tools such as BlenderProc. Open-source releases and shared datasets may further accelerate knowledge exchange and collective progress across the league.

At the same time, the use of standardized lightweight objects simplifies manipulation compared to previous industrial parts with large variability in size, weight, and material. This ensures that most existing manipulators remain viable, particularly in the early seasons. Standardized components also improve global availability, reduce cost, and enable a wide range of product combinations, supporting the vision of adaptive on-demand manufacturing. Future challenges may gradually introduce more realistic components (e.g., wheels, drivetrains) or tools (e.g., drills, screwdrivers), seamlessly extending the workbench tasks.

The workbench track introduces a new focus area: precise object handling and assembly. These tasks reflect key challenges in modern production environments and remain difficult for current robotic systems. To ensure broad participation, multiple strategies are supported. Human–Robot

Interaction (HRI) may be used to compensate for missing manipulation capabilities, reflecting common industrial practice where robots supply parts and humans perform fine assembly. In addition, partnerships across teams and tracks allow groups to combine complementary strengths, enabling higher levels of autonomy than individual teams might achieve alone. This structure encourages collaboration, international exchange, and long-term research progress.

Planning has always been a central element of RoboCup Industrial. However, differences in hardware capabilities and execution reliability have often limited the practical impact of optimized plans. To address this, the EAI-WS introduces a simulation-based planning benchmark that allows fair comparison of planning strategies on a common baseline, independent of physical hardware. Fleet size, arena complexity, and task load can be scaled without additional cost. Until a shared simulation environment is finalized, planning evaluation may remain limited in early events. We explicitly invite teams to contribute to its development, as even simple 2D environments can already enable meaningful benchmarking.

Ultimately, planning solutions are expected to interface with real robots. Community-driven communication standards and collaboration interfaces will therefore play a key role in future seasons. Teams with existing systems may continue to use their custom interfaces during the transition phase.

The new track structure and scoring system are designed to reward both specialization and complete system autonomy. By introducing multiple tiers with gradually increasing complexity, the SML welcomes participants at all career stages. Beginner teams can learn in controlled environments, while advanced teams are challenged with large-scale coordination and throughput optimization. RoboCup thrives on its community, and the SML aims to remain open, inclusive, and ambitious in this spirit.

The 2026 season will serve as a transition phase. Warehouse and planning capabilities from existing @Work and RCLL systems are expected to perform well, while workbench tasks may initially rely more heavily on HRI and partnerships. The expert tier will be treated as a technical challenge in early events, focusing on exploration rather than strict ranking. We strongly encourage teams to form collaborations and contribute to shared interfaces and benchmarks. Such collective efforts are essential for realizing interconnected autonomous factories and preparing individual robotic agents to operate as part of larger, intelligent fleets.

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