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A coherence-driven design framework to analyse process failure for multi-human multi-robot teams in manufacturing

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ABSTRACT

The increasing complexity of collaborative manufacturing systems is driving the transition from dyadic human-robot interaction toward multi-human multi-robot (MH-MR) configurations. In these systems, process performance depends both on individual task execution and on the quality of interactions among multiple agents, with varying degrees of intelligence and autonomy. In such settings, human operators and robotic agents interact through task allocation, control signals, and shared process-state information. However, conventional failure analysis methods, such as Failure Mode, Effects and Criticality Analysis (FMECA), are primarily task-centred and do not fully capture failures arising from interaction-level misalignments. This paper proposes a coherence-driven framework for the design and analysis of MH-MR systems, where failures are interpreted as the result of coherence violations across interacting agents. The methodology is structured as a stepwise process that starts from process decomposition, introduces agent configuration, derives interactions, and identifies critical coherence requirements. Potential coherence violations are then translated into generalized failure mode categories which are subsequently structured using conventional representation tools. The approach is analysed through a case study involving the collaborative assembly of a skateboard performed by two human operators and two robotic agents. The results show that, while execution-level failures remain relevant, additional failure mechanisms emerge from coordination, communication, and collaboration among agents. The proposed framework enables a shift from task-level failure analysis to an interaction-driven design approach, providing a novel tool to support practitioners during the design of MH-MR manufacturing processes.

1. Introduction

The increasing adoption of collaborative robotics in manufacturing is driving a transition from traditional human-robot interaction paradigms toward more complex configurations involving multiple human operators and robotic agents. In this context, multi-human multi-robot (MH-MR) systems are emerging as a key enabler for flexible and adaptive production, particularly in assembly processes where tasks are interdependent and require continuous coordination among agents [1–3].

While human-robot collaboration has been extensively studied in dyadic settings (i.e., one human and one robot), scaling these systems to multi-agent configurations introduces additional complexity [4–6]. In MH-MR systems, multiple agents work simultaneously within a shared workspace, often performing parallel or interdependent tasks [7]. As a result, process performance depends on the correct execution of individual tasks and on the quality of interactions among agents, including coordination, communication, and collaboration [5,8–10].

Existing approaches to process failure analysis in manufacturing are primarily based on task-level representations. Methods such as Failure Mode, Effects and Criticality Analysis (FMECA) are widely used to identify potential failures associated with specific operations, components, or agents, also in human-robot collaboration processes [11–13]. However, these approaches tend to focus on execution-level errors and often assume that failures can be attributed to individual tasks or agents. This assumption becomes limiting in MH-MR systems, where failures frequently emerge from misalignments across interacting agents rather than from isolated errors. Interaction-driven failures, such as lack of synchronization, inconsistent information exchange, or misalignment of

List of Acronyms: HRC, Human-robot collaboration; HRI, Human-robot interaction; HRT, Human-robot teaming; MH-MR, Multi-human multi-robot; FMEA, Failure mode and effects analysis; FMECA, Failure mode, effects, and criticality analysis; RPN, Risk priority number; DFA, Design for assembly.

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objectives, are difficult to capture using conventional task-centred methods. These failures depend on how agents align in time, space, and on the mutual understanding during process execution [14–16]. The proposed framework supports the early identification of interaction-level vulnerabilities during process design, before these vulnerabilities are translated into control requirements, interface specifications, or mitigation mechanisms.

To address this limitation, this paper introduces a coherence-driven framework for the design and analysis of process failure in MH-MR systems in manufacturing. The central idea is to interpret failures as the result of coherence violations across interacting agents. By focusing on interactions rather than individual tasks, the proposed approach enables the identification of failure mechanisms that are not captured by traditional methods.

The framework is structured as a stepwise methodology that starts from process decomposition, introduces agent configuration, derives interactions, and analyses coherence requirements across agents. Potential coherence violations are then identified and translated into failure mode categories which can be subsequently structured using conventional representation tools such as FMECA. The proposed approach is herein applied to a case study involving the collaborative assembly of a skateboard, performed by a team of two human operators and two robotic agents.

The paper is structured as follows. Section 2 reviews the relevant literature on human-robot collaboration and MH-MR systems. Section 3 introduces the conceptual foundations of the proposed framework and the related methodological approach. Section 4 presents the coherence-driven methodology. Section 5 describes the case study and its application. Section 6 discusses the results and implications while Section 7 summarises the main conclusions.

2. Literature review

Over the past decade, human-robot collaboration (HRC) has been investigated increasingly as a key enabler of Industry 5.0, particularly in manufacturing and assembly contexts where human flexibility is combined with robotic precision and repeatability [1–3,17]. Much of the industrial literature still considers HRC within a dyadic paradigm (1H-1R), thus involving one human operator and one collaborative robot. This literature tends to focus on modelling human behaviour, cognition, and decision-making in collaborative workstations [4]. These studies highlight persistent gaps related to safety, efficiency, and context-aware system design. However, recent contributions signal a conceptual shift from human-robot collaboration (HRC) as a dyadic interaction towards human-robot teaming (HRT), in which the team becomes the unit of analysis [8,18]. This transition involves a fundamental change in evaluation constructs and system vulnerabilities. Team-based configurations introduce novel dynamics relating to coordination, communication and shared understanding that cannot be attributed to the performance of individuals or robots alone. Works on HRT explicitly identify scalability, communication, modelling of human behaviour, long-term interaction, benchmarking and psychosocial factors as major research challenges [6]. In particular, the scalability of multi-human multi-robot (MH-MR) configurations is recognised as a critical open problem. As collaborative systems expand beyond dyads, traditional evaluation and design methodologies may no longer be adequate [7].

In manufacturing, MH-MR scenarios involving multiple humans and cobots are already emerging, for example in assembly lines where they operate at shared stations or perform joint tasks [19]. Nevertheless, the majority of industrial research still considers humans and robots as allocable resources within optimisation models rather than coordinated team members, whose interaction quality influences process robustness. Traditionally, the evaluation of HRC systems has relied on metrics such as productivity, efficiency, ergonomics and workload [17,20]. While these metrics remain relevant, they are insufficient to capture the dynamics of multi-agent collaboration. Gervasi et al. [17] proposed a multidimensional framework for evaluating HRC configurations that introduces latent dimensions such as autonomy, information exchange, team organisation, human factors, ethics, and cybersecurity. An additional key variable in assessing interaction quality is fluency, which is defined as the extent to which the actions of humans and robots are coordinated smoothly and efficiently [9]. Objective fluency metrics include human and robot idle times, concurrent activity, and functional delay, while subjective metrics capture perceived coordination quality. However, Hoffman [9] explicitly notes that existing fluency measures are largely validated in dyadic settings and do not adequately address larger teams, role asymmetries, or uncertainty propagation. To bridge this gap, Riedelbauch et al. [10] propose a holistic benchmarking framework for human-cobot teams that integrates productivity, safety, flexibility, job quality and psychological factors. Together, these studies suggest that the quality of collaboration in multi-agent systems depends on higher-level constructs such as cognitive alignment, operational continuity, and socio-technical integration.

In manufacturing contexts, the effective implementation of collaborative systems is closely tied to process design and task allocation. Studies on HRC mainly focus on task allocation and emphasise the importance of task difficulty and complexity when assigning operations to humans or robots [21–23]. These criteria are often employed to optimise productivity and ergonomic outcomes. Misallocation can result in delays or conflicting actions when multiple agents interact simultaneously. Structured methodologies for converting traditional workstations into collaborative ones have been suggested, incorporating task analysis, ergonomic evaluation, layout design and simulation-based validation [24]. These frameworks have been shown to improve fluency and cycle time in collaborative scenarios [25]. However, in MH-MR configurations, complexity affects not only performance, but also interaction, coordination and synchronisation quality. In manufacturing research, few contributions explicitly address MH-MR-like scenarios. For example, Nourmohammadi et al. [19] propose an ALBP-HRC model that explicitly allows for the presence of multiple humans and robots at the same work station, incorporating joint tasks. In this regard, Mao et al. [26] study multi-manned assembly lines integrated with collaborative robots, addressing issues such as task allocation, worker assignment, robot allocation and resource scheduling within a unified optimisation framework. Similar studies incorporate multi-type cobots, collaborative modes and workforce heterogeneity [27]. While these approaches successfully capture resource-level complexity, they rarely identify interaction breakdowns and related potential process failures. In this regard, Ma et al. [5] argue that multi-human, multi-robot teams require metrics that extend beyond classical human-robot interaction (HRI) performance measures and that are oriented towards teamwork. Drawing on cognitive systems engineering, they propose metrics that capture shared mental models, situational awareness and coordination processes [5,8]. However, a systematic methodology to identify process failures specific to MH-MR manufacturing processes is still lacking. In this regard, the paper answers the following research question: *"How can manufacturing process design in multi-human multi-robot (MH-MR) teams be supported by systematically identifying failures arising from interactions among agents?"*

3. Conceptual foundations of the coherence-driven design framework for MH-MR systems

Multi-human multi-robot (MH-MR) systems are characterized by the presence of multiple human operators and robotic agents jointly performing interdependent tasks within a shared process [28]. Unlike dyadic human-robot collaboration, these systems involve distributed responsibilities, parallel activities, and increased interaction complexity, making team-level behaviour a central aspect of system performance [6].

3.1. Conceptual assumptions and key definitions

The proposed framework is based on three conceptual assumptions. First, agents are interpreted as process-executing entities within a manufacturing system. The term includes both human operators and robotic systems, without implying that robots possess subjective intentions, goals, or cognitive understanding. For robotic agents, behaviour is defined by programmed actions, control states, signals, and task constraints. Second, coherence is mainly considered a qualitative design construct. It describes the alignment conditions that must hold among agents, tasks, information flows, and process states for an interaction to be executed correctly. Third, a coherence violation occurs when one or more of these alignment conditions are not satisfied, potentially generating process failures at the interaction level.

The following definitions are adopted in this work to describe interactions and failure mechanisms in multi-human multi-robot systems:

- **Multi-Human Multi-Robot (MH-MR) team:** a Multi-Human Multi-Robot (MH-MR) team is a structured group composed of at least three heterogeneous agents, including both human and robotic members, working together towards a shared goal through continuous interaction, information exchange, effective coordination, clear task allocation, and dynamic collaboration between agents throughout the production process [28]
- **Communication** refers to the exchange of information between agents, including signals, feedback, and task-related data. Communication enables agents to update their understanding of the process state and enables robotic agents or controllers to receive, transmit, or update relevant process-state information [5].
- **Coordination** is defined as the alignment of actions in time and sequence among agents. Coordination ensures that interdependent tasks are executed in the correct order and with appropriate timing, particularly in the presence of task dependencies and synchronization requirements [5].
- **Collaboration** indicates the joint execution of tasks by multiple agents toward a shared goal. Collaboration involves mutual dependence and often requires simultaneous or tightly coupled actions among agents [5].
- **Coherence** refers to the degree to which the elements involved in an interaction, such as assigned task objectives, available information, timing, spatial conditions, roles, and process-state interpretation, remain mutually consistent and compatible with the expected process progression. In this work, coherence is used as a qualitative design construct to identify interaction-level vulnerabilities in MH-MR manufacturing processes.
- **Process failure** represents a consequence of a coherence violation among interacting agents. This does not exclude conventional execution-level failures, but extends failure analysis to misalignments arising from coordination, communication, and collaboration mechanisms.

3.2. Methodological development

The coherence-driven framework was developed through an expert-informed modelling process. The conceptual development was carried out through joint assessment sessions involving a group of six experts: three academics, including professors and researchers, and three professional process engineers with experience in collaborative robotics, manufacturing process design, quality engineering, and multi-agent systems. The discussion was structured around three main questions: (i) which interaction-related mechanisms become critical when moving from dyadic HRC to MH-MR systems? (ii) which alignment conditions must hold for communication, coordination, and collaboration to support correct process execution? and (iii) how can violations of these conditions be translated into process failure mechanisms that are meaningful from a manufacturing engineering perspective?

During the first stage, the expert group examined constructs from human-robot collaboration, human-robot teaming, multi-agent interaction, cognitive systems engineering, and process failure analysis. Particular attention was given to communication, coordination, collaboration, shared awareness, synchronization, task interdependence, role allocation, control-state feedback, and failure propagation. These constructs were selected because they describe recurring sources of interaction complexity in MH-MR manufacturing systems.

During the second stage, the selected constructs were reinterpreted from a manufacturing process-design perspective. In the proposed framework, robotic behaviour is interpreted in terms of programmed task objectives, control logic, operational states, sensor feedback, and predefined action constraints. Human-related constructs, such as awareness and role interpretation, are considered only with reference to human operators and to the information made available through procedures, interfaces, and robot states. However, the framework remains compatible with future robotic agents that likely will be characterized by higher levels of intelligence and decision autonomy.

During the third stage, the expert group progressively organized the selected constructs into five coherence features: goal coherence, information coherence, temporal coherence, spatial coherence, and cognitive coherence. These features were considered sufficiently distinct and able to describe different alignment requirements in MH-MR interactions.

The conceptual structure was refined through a discussion inspired by Delphi-like procedures [29]. When divergent interpretations emerged, the experts were asked to explicitly state the reasons for disagreement. The definition of the coherence features and their boundaries were then discussed, reformulated, or clarified until a shared interpretation was reached and ambiguity among overlapping concepts was reduced.

The resulting framework should therefore be interpreted as a qualitative and expert-informed design methodology. Its purpose is to provide a traceable conceptual structure for identifying where interaction misalignments may arise and how they can be translated into failure mode categories during early process design. The same methodological approach was followed during the application of the framework to the case-study.

4. Coherence-driven MH-MR design framework

A structured methodology called coherence-driven design framework has been introduced to analyse emergent failures of multi-human, multi-robot (MH-MR) systems in manufacturing environments. Such methodology is applied in the early design and process planning phases, when manufacturing processes are configured, agents are assigned and interaction structures are defined, prior to execution. The main challenge in this context is anticipating how interdependencies among agents may generate process failures. The framework is intended to be applied once a preliminary process description and a candidate MH-MR system concept are available. Therefore, it does not require the complete definition of low-level control logic, detailed robot trajectories, fixtures, or interlock mechanisms. At this stage, the process must be detailed enough to identify elementary tasks, candidate agents, task dependencies, and expected interaction points. The appropriate level of analysis is the elementary task that can be assigned to one or more agents and that may generate dependencies, handovers, information exchanges, shared-space conditions, or synchronization requirements. An elementary task denotes the smallest meaningful work element considered for process planning and agent allocation. Consistently with assembly process planning terminology, elementary tasks are intended to represent assignable operations that can be connected through logical and temporal precedence relations [30–32].

In practice, a preliminary process is first defined, while process design and manufacturing-system design are then refined iteratively as candidate agents, layout constraints, interfaces, fixtures, and control requirements become progressively available. In this context, this

methodology is intended to support the systematic identification of potential process weaknesses from the early stages of MH-MR system design. Based on the conceptual development described above, the coherence-driven design framework is operationalized through six sequential steps: (i) process decomposition, (ii) agent configuration, (iii) interaction mapping, (iv) coherence-based analysis, (v) failure mode category identification and (vi) representation layer using FMECA analysis. Each step produces a structured output that serves as input for the next stage, ensuring continuity from the initial process description to the final representation of failure modes. The initial steps focus on modelling the process and configuring the involved agents. The intermediate steps focus on deriving and analysing interactions, paying particular attention to the coherence conditions required for stable execution. The final steps translate coherence breakdowns into recurrent failure mode categories and organize them into a structured representation, e.g., FMECA [33–35], that is suitable for process design (see Fig. 1).

4.1. Process decomposition

The first step of the proposed framework focuses on the decomposition of the manufacturing process into its fundamental elements, i.e., elementary tasks. This step is required to establish a structured and agent-independent representation of the process, which serves as the basis for subsequent analysis. It allows the process to be represented in terms of phases and tasks, together with their logical and temporal relationships. In this work, a process phase denotes a macro-stage of the assembly process, usually associated with the assembly of a subsystem, module, or functional portion of the product.

The input of this step consists of a process description, which may include assembly instructions, workflow diagrams, or task lists. Based on this information, the process is structured into a Process Structure Model, which includes:

- the identification of process phases,
- the definition of elementary tasks,
- and the specification of task dependencies.

To support the explanation of the proposed methodology, a simplified collaborative assembly scenario is considered. The example is based on the assembly of a simple mechanical component (see Fig. 2) composed of three parts: a base plate, a square flange, and an oval flange. The three components are assembled in a stacked configuration, where the square flange is placed on top of the base, followed by the oval flange. The final assembly is obtained by fastening the three components together using two bolts. The process is composed of a single phase "A" composed of 4 tasks (A.1, A.2, A.3 and A.4) involving two human operators (H1, H2) and two robotic agents (R1, R2). The identification of the elementary task derives from the Design For Assembly approach [36]. Hence, the tasks are organized sequentially, with each operation depending on the completion of the previous one (see Table 1).

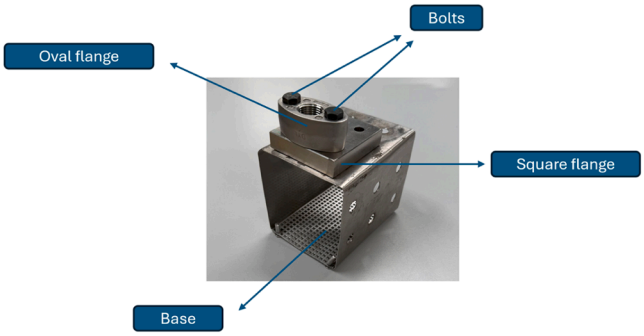


Fig. 2. The assembled mechanical component.

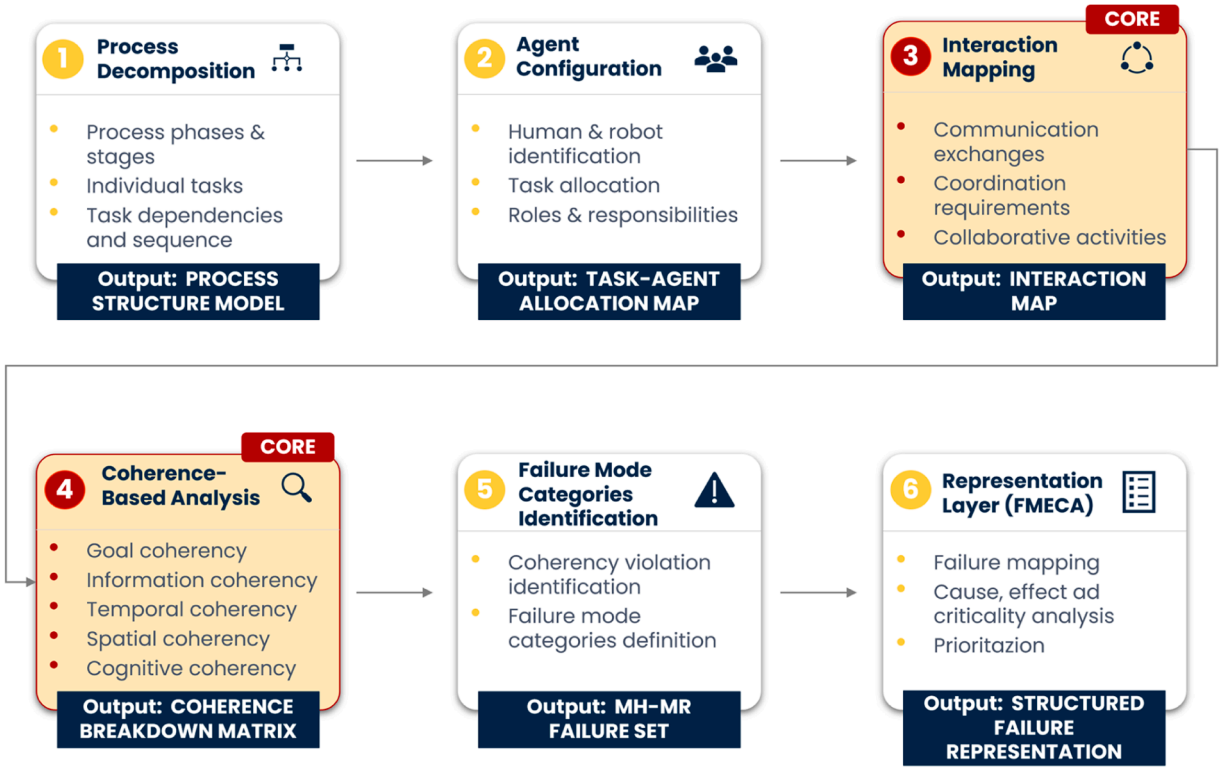


Fig. 1. The six steps of the coherence-driven design framework: 1) process decomposition, 2) Agent configuration, 3) Interaction mapping, 4) Coherence-based analysis, 5) Failure mode categories identification and 6) Representation layer (FMECA).

Table 1
Process Structure Model for the illustrative example.

Phases	Elementary task	Description	Predecessor
A	A.1	Position "Base"	-
A	A.2	Place "square flange" on "Base"	A.1
A	A.3	Place "oval flange" on "square flange"	A.2
A	A.4	Join the three components using two bolts	A.3

4.2. Agent configuration

The second step of the proposed framework focuses on the configuration of agents within the process. Building upon the process structure (Step 1), this step introduces human and robotic agents and assigns them to the identified tasks. In MH-MR systems, multiple agents with different capabilities may be involved in the execution of the same task or in interdependent tasks. The objective of this step is to define the allocation of agents to tasks and to specify their roles and responsibilities within the process basing on their capabilities. At this stage, agent capabilities are considered at a qualitative planning level to determine feasible task assignments. For human operators, relevant capabilities include manual dexterity, visual inspection, alignment, decision-making, and fastening operations. For robotic agents, relevant capabilities include repeatable positioning, holding, pick-and-place, and component presentation within the programmed workspace.

Based on the process structure model, agents are introduced and mapped to tasks, resulting in a Task-Agent Allocation Map, which includes:

- the identification of human and robotic agents involved in the process,
- the assignment of agents to each task,
- and the definition of roles and responsibilities for task execution.

This configuration introduces both individual and joint task execution, as well as interactions between human-human and human-robot agents. At this stage, interactions among agents are not explicitly modelled but implicitly emerge from task allocation and dependencies. The output of this step is the Task-Agent Allocation Map, which provides a structured representation of how tasks are distributed among agents and serves as the basis for deriving interactions in the following step. The allocation reported in Table 2 is based on simple feasibility criteria and it is not the result of an optimization procedure. Table 2 shows the task allocation for the illustrative example.

Task allocation between human and robotic agents can be performed according to different criteria, including performance optimization, ergonomics, or workload balancing, as widely addressed in the literature [37,38]. While task allocation has been extensively studied in collaborative assembly systems, the objective of the proposed methodology is not to optimize task assignment, but to analyse the implications of a given allocation in terms of interactions and coherence.

4.3. Interaction mapping

The third step focuses on the identification and mapping of interactions among agents. Based on the task-agent configuration (Step 2), interactions are derived by task dependencies and joint task execution.

Table 2
Task-agent allocation map for the illustrative example.

Phases	Elementary tasks	Duration [s]	H1	H2	R1	R2
A	A.1	5	✓		✓	
A	A.2	8	✓			✓
A	A.3	8		✓	✓	
A	A.4	25	✓	✓	✓	

In MH-MR systems interactions do not exist independently of the process structure. They emerge from how tasks are allocated and related to each other. Basing on the "three C's" (3Cs) model proposed by Ma et al. [5], interactions can be characterized according to three fundamental dimensions previously defined in Section 3: communication, coordination, and collaboration. The 3Cs are used to classify the type of interaction among agents, whereas coherence describes the alignment conditions required for that interaction to be correctly executed. In other words, communication, coordination, and collaboration describe what kind of interaction occurs, while coherence describes what must remain aligned within that interaction. Based on task allocation map (Table 2), interactions are identified by analysing:

- task dependencies between agents, which generate coordination requirements.
- information needs between agents, which generate communication exchanges.
- joint task assignments, which generate collaboration activities.

The output of this step is an Interaction Map, which identifies interactions among agents and labels them as communication, coordination and collaboration.

In the illustrative example, interactions emerge from two main conditions: (i) transitions between tasks assigned to different agents, and (ii) tasks requiring simultaneous execution by multiple agents. Table 3 reports the resulting Interaction Map.

The interaction map highlights the coexistence of collaboration, coordination, and communication mechanisms within the process. Collaborative interactions dominate the execution of tasks involving physical co-manipulation, such as I1, I3, I5 and I7, where human and robotic agents operate simultaneously on the same components. These interactions require tight coupling in terms of action execution and workspace sharing. Coordination interactions are mainly associated with task sequencing, as observed in I2. Communication interactions emerge at points where explicit information exchange is required to synchronize agents. In particular, transitions such as I4 and I6 require agents to communicate readiness and confirm process progression before proceeding to the next step.

Table 3
Interaction map for the illustrative example showing the interaction identification, the assembly process step involved, the related agents involved, the type of interaction and a qualitative description.

Interaction ID	Process step	Agents involved	Type	Description
I1	A.1	R1 - H1	Collaboration	Robot holds component A while human verifies alignment
I2	A.1 → A.2	H1 - R2	Coordination	Completion of A.1 enables execution of the next task
I3	A.2	R2 - H1	Collaboration	Robot positions component B while human checks alignment
I4	A.2 → A.3	H1 - H2	Communication	H1 communicates readiness to H2 before introducing component C
I5	A.3	H2 - R1	Collaboration	Human places component C while robot stabilizes A+B
I6	A.3 → A.4	H1 - H2	Communication	Agents exchange readiness before final assembly
I7	A.4	H1 - H2 - R1	Collaboration	Multi-agent joint execution of the final joining task

Overall, the interaction map shows that interactions are not uniformly distributed across the process but are concentrated in specific stages, particularly where agents must synchronize their actions or exchange information. This representation provides the basis for the subsequent coherence analysis.

4.4. Coherence analysis

The fourth step of the framework focuses on the analysis of coherence across the interactions identified in Step 3. The purpose of this step is to determine which coherence conditions are critical for correct execution and to identify the possible ways in which such conditions may be violated. In MH-MR systems, process reliability depends on the alignment of agents during execution [7]. However, not all coherence features are equally relevant for every interaction. Instead, for each interaction, only the coherence features that are critical for successful execution are considered.

The input of this step is the Interaction Map obtained in Step 3. For each interaction, the process designer identifies which coherence features are critical for correct execution. These features can be intended as both qualitative and quantitative design categories used to distinguish different forms of interaction misalignment. In the present formulation, they are primarily assessed qualitatively, although the assessment may be supported by quantitative evidence when process data, time thresholds, system logs, or control-state information are available. In detail they are:

- **Temporal coherence** refers to the compatibility between the timing of an interaction and the precedence relations, time windows, synchronization requirements, and temporal validity of information. It is relevant when an interaction depends on the correct start time, completion time, order of execution, simultaneous availability of agents, or timely response to signals.
- **Spatial coherence** refers to the compatibility among positions, trajectories, distances, shared zones, accessibility conditions, and workspace constraints during an interaction. It is relevant when agents, components, tools, fixtures, or handover areas physically interact or share the same operational space.
- **Information coherence** refers to the compatibility between the information required, generated, transmitted, received, and used during an interaction. This includes readiness signals, system feedback, confirmation messages, task-state information, technical data, and control inputs. Information coherence is relevant when incorrect, incomplete, ambiguous, outdated, or unreadable information may affect process execution.
- **Cognitive coherence** refers to the compatibility between human operators' understanding of the process state, task progression, roles, responsibilities, expected actions, and the information provided by procedures, interfaces, system feedback, and robot states. In the present work, this feature does not imply cognitive understanding by robotic agents. However, this assumption may evolve in future scenarios involving robotic agents with higher levels of intelligence and decision autonomy, provided that their contribution remains interpretable through observable decision logic, operational states, and information exchange.
- **Goal coherence** refers to the alignment between local actions, local objectives, and global process priorities. For robotic agents, this refers to programmed task objectives or control targets, not to subjective intentions. Goal coherence is relevant when agents must converge toward the same production outcome while preserving process priorities such as safety, quality, validation, and correct task completion.

Based on these rules, the process designer identifies, for each interaction, the coherence features whose violation could compromise process execution. To support the application of the qualitative assessment, Table 4 provides decision rules for identifying when each coherence feature is relevant and how the corresponding violation can be recognized.

The qualitative assessment of coherence requirements is particularly useful for temporal, spatial, and information coherence. Temporal coherence can be examined through observed or planned task durations, waiting times, overlaps between actions, response times, and compliance with predefined time windows. Spatial coherence can be supported by layout data, distances among agents, accessibility conditions, workspace occupancy, reachability, and interference or congestion conditions. Information coherence can be supported by the presence, completeness, consistency, and confirmation of signals, feedback, and process-state information. These quantities are not introduced as universal metrics or fixed thresholds, since acceptable values depend on the specific process, equipment, layout, control logic, and safety requirements. Rather, they provide measurable evidence that makes more traceable the expert-based identification of required coherence conditions and possible violations. Some explicative examples are reported in the analysis of the case study.

Table 4
General decision rules for identifying critical coherence requirements and violations.

Coherence feature	Formal-operational definition	Examples of specific coherence requirements	Typical violation evidence
Temporal coherence	Compatibility between the timing of the interaction and precedence relations, time windows, synchronization requirements, and temporal validity of information.	Task precedence respected; interaction inside time window; agents simultaneously available; information temporally fresh; response within maximum time.	Waiting time; delayed input; premature action; idle time; missed synchronization; expired information.
Spatial coherence	Compatibility among positions, trajectories, distances, shared zones, accessibility conditions, and workspace constraints.	Non-interfering trajectory; part accessible; zone not congested; safety distance respected; signal/object visible or perceivable.	Interference; unstable handover; wrong positioning; workspace conflict; inaccessible component.
Information coherence	Compatibility between information required, generated, transmitted, received, and used during the interaction.	Technical data correct; technical data complete; state semantically univocal; data updated; format readable; source and validation traceable.	Missing input; unclear feedback; absent confirmation; inconsistent robot state; outdated or unreadable information.
Cognitive coherence	Compatibility between human operators' mental models, expectations, perceived intentions, role interpretation, and predictability of system behaviour.	Action predictable; signal understandable; intention clear; roles clear; workload compatible; human mental model of robot state updated.	Role confusion; wrong readiness perception; misunderstanding of task state; unexpected robot behaviour.
Goal coherence	Alignment between local actions, local objectives, and global process priorities.	Safety over cycle time; quality gate preserved; completion, validation, and release clearly distinguished; decision authority clear; anomaly response consistent with priorities.	Wrong task objective; inconsistent assembly target; incorrect process progression; priority conflict between productivity, safety, or quality.

These general rules are intended to guide expert-based assessment. It is important to underline that these features may coexist within the same interaction, although they describe different alignment requirements (see Table 4). At this stage, the analysis remains focused on possible coherence violations, without yet translating them into failure modes. Hence, the output of this step is a Coherence Breakdown Matrix, which associates each interaction with:

- the critical coherence features,
- and the corresponding possible coherence violations.

Table 5 reports the resulting Coherence Breakdown Matrix for the illustrative example. Collaborative interactions, such as I1, I3, I5 and I7, are characterized by strong spatial, temporal, and cognitive coherence requirements. In these tasks, agents operate simultaneously within a shared workspace and must coordinate both their actions and their understanding of the task. The final task (I7) represents the most critical case, as it involves multiple agents performing a joint operation, requiring alignment not only in timing and positioning but also in the intended objective of the action.

Coordination interactions, such as I2, are primarily driven by temporal coherence, as correct execution depends on the proper sequencing of tasks. In this case, the main risk is related to incorrect timing or premature execution of the subsequent task. Communication interactions, such as I4 and I6, introduce information-related dependencies. These interactions require agents to exchange explicit signals to align on readiness and process progression. In particular, the transition from A.3 to A.4 (I6) also involves goal coherence, as all agents must share a consistent understanding of the objective before starting the final assembly. In this case, A.4 is the longest task and involves three agents simultaneously (H1, H2, and R1), which makes the associated interaction I7 more exposed to temporal, spatial, and cognitive coherence requirements. Conversely, the shorter sequential tasks A.1-A.3 mainly highlight transition-related coherence requirements, such as the correct sequencing between A.1 and A.2 and the alignment between placement and verification actions in A.2 and A.3.

At this stage, the analysis is limited to identifying possible coherence violations. These represent the conditions under which failures may occur and provide the basis for the failure mode category identification performed in the next step.

4.5. Failure mode category identification

The fifth step of the proposed framework focuses on the identification of failure mode categories. Building upon the Coherence Breakdown Matrix defined in Step 4, this step translates the identified coherence violations into structured failure categories. Failure identification is performed by systematically analysing how the coherence violations identified in Step 4 may affect process execution.

The input of this step is the Coherence Breakdown Matrix obtained in Step 4. For each interaction, the identified coherence violations are interpreted in terms of their impact on execution, and similar effects are grouped into common failure mode categories.

In particular, coherence violations associated with different coherence features give rise to distinct classes of failure:

- Violations of **temporal coherence** may lead to temporal misalignment, delays, or incorrect task sequencing.
- Violations of **information coherence** may lead to inconsistent or incomplete awareness of the system state.
- Violations of **spatial coherence** may lead to physical interference or conflicts in shared workspace.
- Violations of **cognitive coherence** may lead to misinterpretation of the process state or roles, resulting in uncoordinated actions.
- Violations of **goal coherence** may lead to misaligned objectives or inconsistent process progression.

These failure manifestations are then organised into a set of failure mode categories which capture recurring mechanisms through which coherence breakdown affects process execution.

Typical failure mode categories emerging from the analysis include temporal misalignment, coordination breakdown, role ambiguity, asymmetric awareness, and resource conflict.

In the illustrative example, the coherence violations identified in Step 4 can be interpreted in terms of the following failure mode categories:

- **temporal misalignment** in the transition I2, where incorrect sequencing or delayed execution may prevent the proper progression of the process;
- **coordination breakdown** during I3, resulting from misalignment between robot positioning and human verification actions;
- **asymmetric awareness** in the transition I4, caused by missing or ambiguous communication regarding task readiness;
- **resource conflict** during I5, where improper coordination between human and robot may lead to unstable positioning or interference in the shared workspace;
- **goal misalignment** and **asymmetric awareness** in the transition from A.3 to A.4 (I6), when agents proceed without a consistent understanding of the process state or intended objective;
- **coordination breakdown** and **role ambiguity** during the final interaction (I7), where multiple agents must simultaneously perform the joining operation and align both actions and responsibilities.

The output of this step is therefore a MH-MR Failure Set, consisting of categorized failure mode derived from coherence violations (see Table 6).

4.6. Representation layer

The final step focuses on the structured representation of the identified failure modes. Unlike traditional approaches, where tools such as Failure Mode, Effects and Criticality Analysis (FMECA) are used for failure identification, in the proposed framework failure modes are derived from coherence violations. Representation tools are therefore used only to structure and communicate the identified failure modes. Based on the set of Failure mode categories (step 5), each failure mode category is associated with:

Table 5
Coherence breakdown matrix for the illustrative example showing the interaction identification, the assembly process step involved, the related agents involved, the different types of coherence (goal, information, temporal, spatial and cognitive) and the related possible violation.

Interaction ID	Goal	Info	Temporal	Spatial	Cognitive	Possible Coherence Violation
I1	-	-	✓	✓	✓	Misaligned positioning or incorrect stabilization
I2	-	-	✓	-	-	Incorrect sequencing of task execution
I3	-	-	✓	✓	✓	Misalignment between placement and human verification
I4	-	✓	-	-	✓	Missing or ambiguous readiness communication
I5	-	-	✓	✓	✓	Improper placement due to poor coordination
I6	✓	✓	-	-	✓	Incomplete or inconsistent readiness confirmation
I7	✓	-	✓	✓	✓	Unsynchronized actions or unclear role distribution

Table 6
MH-MR failure set showing the interaction identification, the assembly process step involved, the related agents involved, the possible coherence violation, the related failure mode category and its description.

Interaction ID	Process step	Agents involved	Possible Coherence Violation	Failure Mode category	Description
I1	A.1	R1 - H1	Misaligned positioning or incorrect stabilization	Resource conflict	Improper alignment leads to instability during manipulation
I2	A.1 → A.2	H1 - R2	Incorrect sequencing of task execution	Temporal misalignment	Task is executed too early or too late
I3	A.2	R2 - H1	Misalignment between placement and verification	Coordination breakdown	Robot and human actions are not properly synchronized
I4	A.2 → A.3	H1 - H2	Missing or ambiguous readiness communication	Asymmetric awareness	Agents do not share the same understanding of process state
I5	A.3	H2 - R1	Improper placement due to poor coordination	Resource conflict	Misalignment during component positioning
I6	A.3 → A.4	H1 - H2	Incomplete or inconsistent readiness confirmation	Goal misalignment / Asymmetric awareness	Agents proceed without a shared objective or consistent state
I7	A.4	H1 - H2 - R1	Unsynchronized actions or unclear role distribution	Coordination breakdown / Role ambiguity	Multiple agents fail to align actions or responsibilities

- the corresponding process step (interaction or task),
- the failure mode (derived from coherence violation categories),
- and the causes and the resulting effect on process execution.

In this work, a FMECA-like structure is adopted as a reference representation format (see Table 7).

This structured representation highlights how failure mode categories derived from coherence violations can be mapped onto specific process elements. Coordination breakdown emerges as a dominant failure mechanism in joint activities, while temporal misalignment and asymmetric awareness are primarily associated with transitions between tasks. The output of this step is therefore a structured failure representation, which can be used to support further analysis, prioritization, and mitigation strategies.

5. Case-study: the collaborative assembly process of a skateboard

To show the application of the proposed methodology in a controlled MH-MR setting, a case study based on the collaborative assembly of a skateboard is considered. The scenario is designed to represent a multi-human multi-robot (MH-MR) system in which multiple agents operate within a shared workspace while performing interdependent tasks.

5.1. Case-study description

The product assembled during the collaborative assembly consists of a skateboard shown in Fig. 3.

The experimental setup was implemented in a laboratory environment (Mind4Lab, Politecnico di Torino, Italy), where a dedicated workstation was configured to support human-robot collaboration. The system includes two collaborative robotic manipulators (Universal Robots UR3e) and two human operators working in proximity. The collaborative assembly was carried out on a rectangular table of approximately 160 cm × 70 cm, positioned at a height of about 120 cm. The two robotic manipulators were mounted upside down approximately 70 cm above the workbench and were positioned about 60 cm apart. The two human operators worked simultaneously on the same workbench at an approximate mutual distance of 90 cm (see Fig. 4). The central area between the two robots represented the main shared workspace.

The overall configuration follows a symmetric layout: each human-robot pair is assigned to one portion of the product (front and rear) and executes similar operations in parallel. This arrangement enables the observation of both local interactions within each pair and global coordination requirements across the team.

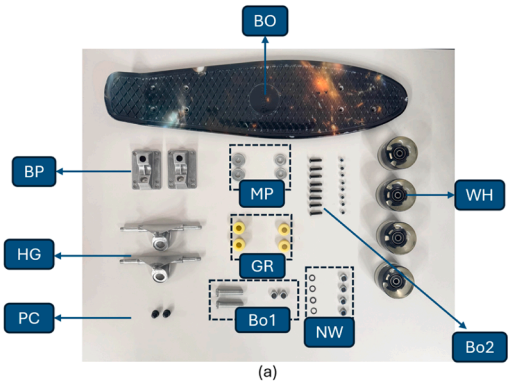
The skateboard is composed of three main subsystems: trucks, wheels, and board. The assembly process is structured into three main phases (see Fig. 5), corresponding to (i) truck assembly (phase A), (ii) wheel mounting on the truck (phase B), and (iii) integration of the truck with the board (phase C). Each phase is further decomposed into elementary tasks, defining the overall process workflow.

5.2. Application of the coherence-driven framework

This case study provides a representative MH-MR scenario, combining parallel execution, shared workspace constraints, and interaction-driven dependencies. As such the proposed coherence-based

Table 7
Structured failure representation (FMECA method) showing the interaction identification, the assembly process step involved, the related agents involved, the process failure mode identified, the related cause and effect and the belonging category.

Interaction ID	Assembly step	Agents involved	Failure Mode Category	Process Failure Mode	Cause	Effect
I1	A.1	R1 - H1	Resource conflict	Misaligned positioning during stabilization	Human correction applied before stable robot positioning	Unstable component positioning
I2	A.1 → A.2	H1 - R2	Temporal misalignment	Incorrect task sequencing	Premature initiation of next task; missing synchronization cue	Delayed or premature execution
I3	A.2	R2 - H1	Coordination breakdown	Misaligned human-robot actions	Inconsistent timing between robot placement and human verification	Incorrect positioning or rework
I4	A.2 → A.3	H1 - H2	Asymmetric awareness	Missing or ambiguous readiness signal	Lack of explicit readiness communication between operators	Inconsistent process state
I5	A.3	H2 - R1	Resource conflict	Improper human-robot coordination	Human action initiated before robot stabilization is complete	Unstable placement or interference
I6	A.3 → A.4	H1 - H2	Goal misalignment	Inconsistent understanding of task objective	Different interpretation of assembly goal before final joining	Incorrect process progression
I7	A.4	H1 - H2 - R1	Coordination breakdown	Unsynchronized multi-agent execution	Lack of shared timing and coordination during joint joining	Assembly error or delay
I7	A.4	H1 - H2	Role ambiguity	Unclear task responsibility	Missing role definition in final joining task	Delayed or missing actions



(a)

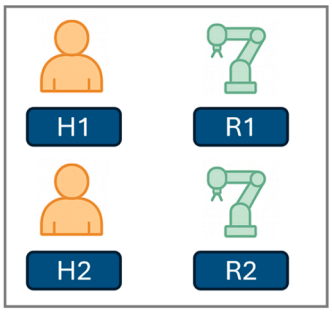


(c)

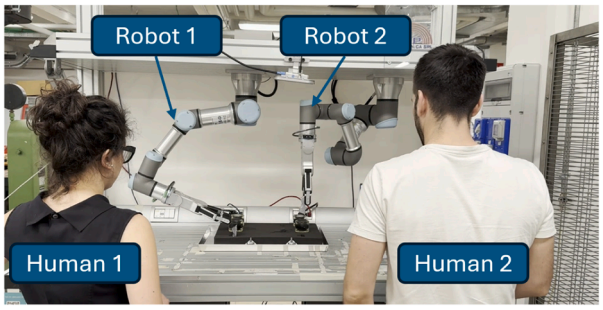
Part ID	Description
BP	Baseplate
HG	Hanger
PC	Pin cup
MP	Metal protector
GR	Grommet
Bo1	Bolt (type 1)
NW	Nut and washers for wheels
Bo2	Bolt (type 2)
WH	Wheels
BO	Board

(b)

Fig. 3. Parts of the skateboard (a) with the related description table (b) and the assembled product (c).



(a)



(b)

Fig. 4. Agents involved in process (a) and related collaborative assembly workstation (b).

framework can be applied to analyze process structure, derive interactions, and identify potential coherence violations.

5.2.1. Step 1 - process decomposition

The first step of the methodology is applied to the skateboard assembly process in order to obtain a structured and agent-independent representation of the workflow.

The input consists of the detailed assembly procedure described in Section 5.1, which defines the sequence of operations required to assemble the skateboard subsystems. Based on this information, the process is decomposed into phases and elementary tasks, and the corresponding precedence relationships are identified.

Table 8 reports the resulting Process Structure Model, where tasks are represented together with their precedence relationships.

At this stage, the process is represented independently of agent allocation and interaction dynamics. This abstraction enables a clear separation between process definition and system configuration, which is essential for the subsequent steps of the methodology.

5.2.2. Step 2 - agent configuration

The second step of the methodology focuses on the configuration of agents within the process. Based on the Process Structure Model (Step 1), human and robotic agents are introduced and assigned to the identified tasks.

The objective of this step is to define how responsibilities are distributed among agents and to explicitly distinguish between human operators and robotic agents. This distinction is particularly relevant in MH-MR systems, as humans and robots contribute differently to task execution in terms of capabilities, flexibility, and interaction requirements. Agents are mapped to tasks, resulting in a Task-Agent Allocation Map provided in Table 9, that specifies which agents are responsible for each operation. In the considered case study, the system is composed of four agents: two human operators (H1, H2) and two robotic agents (R1, R2). The configuration follows a symmetric structure, where each human-robot pair operates on a different portion of the product. In Table 9, checkmarks indicate agent involvement at the elementary task level. The task durations reported in Table 9 were derived from previous experimental trials conducted on the same skateboard assembly procedure and are used here as representative execution times for the case-study analysis.

The resulting configuration highlights a clear distribution of responsibilities between human and robotic agents. Robotic agents are primarily assigned to positioning and handling tasks (e.g., A.3, B.2, B.10, C.1), while human operators perform assembly, alignment, and verification operations.

In this specific case study, all tasks involve coordinated participation of multiple agents, either the two human operators or the two human-robot pairs, due to the symmetric layout of the workstation. Although

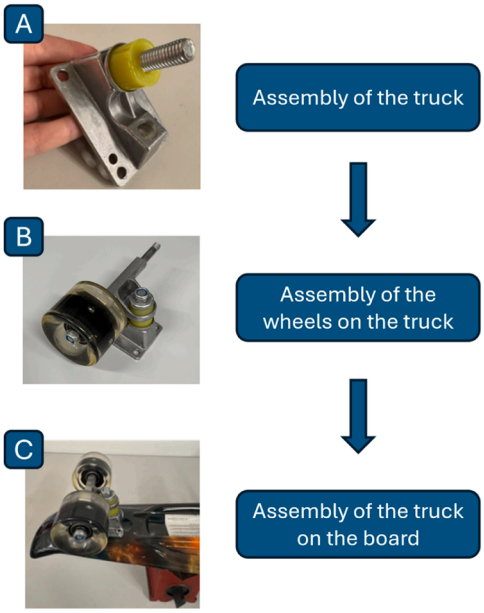


Fig. 5. Three main phases of the collaborative assembly of the skateboard.

Table 8
Process structure model for the collaborative assembly of the skateboard.

Phase	Elementary task	Task Description	Predecessor
A	A.1	Communicate and align on action	-
A	A.2	Send input to cobot	A.1
A	A.3	Pick and place baseplate	A.2
A	A.4	Insert bolt (type 1) into baseplate	A.3
A	A.5	Insert metal protector and grommet	A.4
A	A.6	Insert pin cup and hanger	A.5
A	A.7	Insert grommet and protector	A.6
	A.8	Tighten nut and complete truck	A.7
B	B.1	Send input to cobot	A.8
B	B.2	Pick and place wheel	B.1
B	B.3	Mount wheel on hanger	B.2
B	B.4	Insert washer and tighten nut	B.3
B	B.5	Pick and place second wheel	B.4
B	B.6	Mount second wheel	B.5
B	B.7	Insert washer and tighten nut	B.6
B	B.8	Communicate and align on action	B.7
B	B.9	Send input to cobot	B.8
B	B.10	Verify input received	B.9
C	C.1	Position board	B.10
C	C.2	Place trucks on board	C.1
C	C.3	Insert bolts (type 2) and fix trucks	C.2

robotic tasks are predefined, human execution introduces variability in timing and interaction dynamics, which will play a key role in the emergence of interactions.

At this stage, interactions are not explicitly defined, but they implicitly emerge from the combination of task dependencies and agent allocation, particularly in transitions between human and robot tasks and in synchronization points involving multiple agents.

5.2.3. *Step 3 - interaction mapping*

The third step of the methodology focuses on the identification and mapping of interactions among agents. Based on the Task-Agent Allocation Map (Step 2), interactions are derived from task dependencies and joint task execution.

In the considered case study, interactions arise when tasks performed by different agents are linked through precedence relations, when multiple agents contribute to the same activity, or when synchronization is required to trigger subsequent operations.

Based on the task allocation map, interactions are identified in the Interaction Map provided in Table 10.

Table 9
Task-Agent allocation map for the collaborative assembly of the skateboard.

Phase	Elementary task	Duration [s]	H1	H2	R1	R2
A	A.1	2	✓	✓		
A	A.2	1	✓	✓		
A	A.3	4			✓	✓
A	A.4	2	✓	✓		
A	A.5	3	✓	✓		
A	A.6	4	✓	✓		
A	A.7	4	✓	✓		
A	A.8	9	✓	✓		
B	B.1	1	✓	✓		
B	B.2	3			✓	✓
B	B.3	3	✓	✓		
B	B.4	8	✓	✓		
B	B.5	3	✓	✓		
B	B.6	3	✓	✓		
B	B.7	8	✓	✓		
B	B.8	1	✓	✓		
B	B.9	1	✓	✓		
B	B.10	1			✓	✓
C	C.1	8			✓	✓
C	C.2	10	✓	✓		
C	C.3	22	✓	✓		

The resulting Interaction Map highlights that communication and coordination are primarily associated with transitions between human and robot tasks, particularly when human input is required to trigger robot operations (e.g., I1, I3, I7, I10). Collaboration mainly emerges in tasks performed jointly by human agents, requiring mutual adaptation and shared execution. In addition, several synchronization points are embedded in the process, especially in phases where both human operators must align their actions before enabling robot execution. These points represent critical interaction nodes, as they require simultaneous agreement and coordinated timing among agents.

The Interaction Map provides a structured representation of where interactions occur and how they are characterized, forming the basis for the subsequent coherence analysis.

5.2.4. *Step 4 - coherence analysis*

The fourth step of the methodology focuses on the analysis of coherence across interactions identified in Step 3. The objective is to make explicit the alignment conditions required for correct execution and to identify potential coherence violations that may arise during process operation.

The input of this step is the Interaction Map obtained in Step 3. For each interaction, the required alignment is evaluated according to the coherence features introduced in Section 3:

- goal coherence,
- information coherence,
- temporal coherence,
- spatial coherence,
- cognitive coherence.

Table 11 reports the resulting Coherence Breakdown Matrix for the case study.

The matrix shows that temporal coherence is required in almost all interactions, confirming that synchronization is a dominant requirement in the process. In contrast, information coherence appears only in communication-driven interactions (e.g., I1, I3, I7), while spatial coherence is limited to physical handover and shared workspace tasks (e.g., I4, I5, I12).

Under the sequential representation of the process, the total execution time is 101 s, distributed across phase A, truck assembly, 29 s; phase B, wheel mounting, 32 s; and phase C, truck-board integration, 40 s. Although phase C includes only three elementary tasks, it accounts for approximately 40% of the total process time and corresponds to the most

Table 10
Interaction map for the collaborative assembly of the skateboard.

Interaction ID	Process step	Agents involved	Type	Description
I1	A.1	H1, H2	Communication	Human operators align on readiness and agree on the next action
I2	A.1 → A.2	H1, H2	Coordination	Transition from readiness alignment to task initiation
I3	A.2 → A.3	all	Communication	Human input triggers robot operation
I4	A.3	all	Collaboration	Robot positions component while human prepares for assembly
I5	A.3 → A.4	all	Coordination	Transition from robot positioning to human assembly
I6	A.4-A.8	H1, H2	Collaboration	Human operators jointly assemble truck components
I7	B.1 → B.2	all	Communication	Human input triggers robot placement of wheel
I8	B.2 → B.3	all	Coordination	Transition from robot placement to human mounting
I9	B.3-B.7	H1, H2	Collaboration	Humans perform wheel assembly tasks in coordination
I10	B.8	H1, H2	Communication	Human operators align before next operation
I11	B.9 → B.10	all	Communication	Input signals are sent to robot and verified
I12	C.1	R1, R2	Coordination	Robots position board for assembly
I13	C.1 → C.2	all	Coordination	Transition enabling human placement of trucks
I14	C.2-C.3	H1, H2	Collaboration	Humans jointly align and fix trucks to board

spatially constrained part of the assembly. In this phase, the board is positioned and held in the central area between the two robots where the two human operators work simultaneously. This configuration makes spatial coherence particularly relevant for interactions I12-I14, where robot positioning, board accessibility, human proximity, and shared workspace occupation directly affect the feasibility of the assembly operation. The longest collaborative sequences are I6, corresponding to truck assembly tasks A.4-A.8, with a cumulative duration of 22 s; I9, corresponding to wheel assembly tasks B.3-B.7, with a cumulative duration of 25 s; and I14, corresponding to board-truck integration tasks C.2-C.3, with a cumulative duration of 32 s. These values indicate that the related interactions require sustained alignment between the two human operators over relatively long execution periods. Conversely, information-related actions such as A.2, B.1, B.9, and B.10 each last 1 s. Their criticality is therefore not associated with long execution time, but with the correctness, availability, and unambiguity of the input or confirmation required to trigger or verify the subsequent robot action. Finally, cognitive and goal coherence are mainly associated with human-involved and collaborative tasks, particularly where joint actions or decision alignment are required (e.g., I6, I10).

Based on these data, two simple process-specific indicators can be derived as examples of measurable support for the qualitative coherence assessment. For temporal coherence, a collaborative interaction

Table 11
Coherence breakdown matrix for the collaborative assembly of the skateboard.

Interaction ID	Goal	Info	Temp	Spatial	Cognitive	Possible Coherence Violation
I1	✓	✓	✓	-	✓	Incomplete alignment on readiness or inconsistent shared understanding
I2	-	-	✓	-	✓	Misaligned task start or lack of synchronization between operators
I3	-	✓	✓	-	-	Incorrect or delayed input to robot
I4	-	-	✓	✓	✓	Misalignment between robot positioning and human preparation
I5	-	-	✓	✓	-	Improper handover between robot and human
I6	✓	-	✓	-	✓	Unsynchronized actions or misaligned task objective
I7	-	✓	✓	-	-	Delayed or incorrect robot activation
I8	-	-	✓	✓	-	Misaligned transition from robot to human execution
I9	-	-	✓	-	✓	Lack of synchronization between human agents
I10	✓	✓	✓	-	✓	Incomplete alignment before next operation
I11	-	✓	✓	-	-	Incorrect or missing input confirmation
I12	-	-	✓	✓	-	Misalignment between robot positioning actions
I13	-	-	-	✓	✓	Misalignment in positioning and readiness
I14	-	-	✓	✓	✓	Inconsistent execution or unclear coordination

duration share can be calculated as the ratio between the cumulative duration of a collaborative interaction and the total process duration. Accordingly, I6 accounts for 22/101 s, corresponding to 21.8% of the total process time; I9 accounts for 25/101 s, corresponding to 24.8%; and I14 accounts for 32/101 s, corresponding to 31.7%. These values support the identification of I14, I9, and I6 as interactions requiring sustained temporal alignment. For spatial coherence, a shared-workspace exposure ratio can be calculated as the ratio between the time spent in the central shared workspace and the total process duration. Since phase C lasts 40 s out of 101 s and is performed in the most spatially constrained shared area, this ratio is equal to 39.6%. This value supports the identification of spatial coherence as critical for interactions I12-I14. These indicators are intended as process-specific quantitative evidence supporting the qualitative assessment.

5.2.5. Step 5 - failure mode category identification

The fifth step of the methodology focuses on the identification of failure mode categories starting from the coherence violations highlighted in Step 4.

The objective of this step is to translate interaction-specific coherence violations into generalized failure mode categories that can describe recurring vulnerabilities in the MH-MR process. This allows moving from local interaction breakdowns to a more structured interpretation of process-level risks.

Based on this representation, each possible coherence violation is examined in terms of its consequences on task execution, and the resulting effects are grouped into recurring failure categories.

Table 12 reports the resulting MH-MR Failure Set for the skateboard assembly case study.

The failure set shows that coordination breakdown is the most recurrent failure mode category, appearing across multiple interactions, particularly in collaborative tasks and transitions between agents. Temporal misalignment is mainly associated with robot-triggered interactions, where execution depends on timely human input, while asymmetric awareness is confined to communication steps, reflecting issues in information exchange and state alignment.

In addition, resource conflicts are limited to handover and positioning interactions, and goal misalignment and role ambiguity emerge mainly in tasks involving human collaboration, highlighting that such failures are strongly dependent on multi-agent coordination rather than on individual task execution.

5.2.6. Step 6 - representation layer

The final step of the methodology focuses on the structured representation of the failure mode categories identified in Step 5. For the skateboard assembly case study, this step organizes the MH-MR Failure Set into a format suitable for analysis, communication, and prioritization.

The input is the MH-MR Failure Set obtained in Step 5. In addition, each failure is characterized through Severity (S), Occurrence (O), and Detection (D) indices. These indices are often combined into a Risk Priority Number (RPN), which provides a synthetic indicator to support the prioritization of failure modes and guide decision-making in process design and improvement. Different formulations of the RPN exist, while one of the most common approaches is to calculate RPN as $RPN = S \times O \times D$. However, it is well known that this aggregation may introduce compensatory effects and limitations, as discussed by Franceschini and Galetto [33]. In this study, S-O-D values were evaluated through discussion sessions involving a panel of domain experts with experience in MH-MR collaboration, process quality, and collaborative system design. By following the approach proposed by Franceschini and Galetto [33], Severity (S), Occurrence (O), and Detection (D) are evaluated on a qualitative scale from 1 to 10, where higher values indicate higher severity, higher likelihood of occurrence, and lower detectability, respectively.

Table 13 reports the resulting FMECA analysis for the MH-MR failures within the skateboard assembly case study.

Based on the RPN values, the most critical failure mode is the coordination breakdown during truck assembly tasks A.4 - A.8 (I6, RPN = 48), due to the combined effect of moderate severity, occurrence, and detectability. Resource conflicts during handover or positioning (I5 and I13, RPN = 40) and goal misalignment during truck assembly (I6, RPN = 40) also emerge as relevant priorities. These results suggest that design improvements should focus on explicit synchronization cues, clearer task objectives, improved handover conditions, and feedback mechanisms supporting shared readiness.

5.3. FMECA for 1H-1R

To complement the coherence-driven analysis introduced in the previous sections, a failure analysis is conducted considering a dyadic human-robot collaboration (1H-1R) configuration.

In the dyadic configuration, a single human operator interacts with a single robotic agent, and the process can be analyzed by focusing on individual tasks and their execution. Under these conditions, failure analysis can be effectively performed using a conventional FMECA approach, where failure modes are associated with specific process steps and attributed to individual agents or to their direct interaction. Unlike the proposed methodology, which focuses on interactions across multiple agents, the dyadic FMECA operates at the execution level, identifying errors related to task performance, handling, and procedural correctness. Each failure mode is described in terms of causes, effects, responsible agent, and Severity (S), Occurrence (O), and Detection (D) indices. Table 14 reports the resulting FMECA for the dyadic configuration. The elementary tasks are those defined in Table 8 according to the Design for Assembly approach proposed by Boothroyd [36].

Table 12
MH-MR failure set for the collaborative assembly of the skateboard.

Interaction ID	Process step	Agents involved	Possible Coherence Violation	Failure Mode category	Description
I1	A.1	H1, H2	Incomplete alignment on readiness	Asymmetric awareness	Operators start with inconsistent understanding of process state
I2	A.1 → A.2	H1, H2	Misaligned task start	Coordination breakdown	Operators do not synchronise the beginning of the process
I3	A.2 → A.3	all	Incorrect or delayed input	Temporal misalignment	Robot action triggered at wrong time
I4	A.3	all	Misalignment in positioning	Coordination breakdown	Human and robot actions not aligned
I5	A.3 → A.4	all	Improper handover	Resource conflict	Instability during robot-human transition
I6	A.4-A.8	H1, H2	Unsynchronized actions	Coordination breakdown	Human actions not aligned in timing
I6	A.4-A.8	H1, H2	Misaligned task objective	Goal misalignment	Incorrect assembly outcome
I7	B.1 → B.2	all	Incorrect activation	Temporal misalignment	Robot placement occurs at wrong time
I8	B.2 → B.3	all	Misaligned transition	Coordination breakdown	Robot-to-human handover not synchronized
I9	B.3-B.7	H1, H2	Lack of synchronization	Coordination breakdown	Humans operate with inconsistent timing
I10	B.8	H1, H2	Incomplete alignment	Asymmetric awareness	Operators not aligned before action
I11	B.9 → B.10	all	Missing or incorrect confirmation	Asymmetric awareness	Robot operates with incorrect state information
I12	C.1	R1, R2	Misaligned positioning	Coordination breakdown	Robots place components inconsistently
I13	C.1 → C.2	all	Misaligned positioning	Resource conflict	Incorrect placement affects assembly
I14	C.2-C.3	H1, H2	Unclear coordination	Role ambiguity	Responsibility not clearly defined

Table 13
FMECA analysis of the collaborative assembly of the skateboard.

Interaction ID	Process step	Agents involved	Failure Mode Category	Failure Mode	Cause	Effect	S	O	D	RPN
I1	A.1	H1, H2	Asymmetric awareness	Inconsistent readiness alignment	Lack of explicit synchronization or unclear readiness cues	Incorrect process start	2	4	2	16
I2	A.1 → A.2	H1, H2	Coordination breakdown	Unsynchronized task initiation	Absence of coordination mechanism between operators	Delayed or premature execution	2	3	3	18
I3	A.2 → A.3	all	Temporal misalignment	Missing or delayed input	Human error or unclear triggering interface	Incorrect robot activation	3	3	4	36
I4	A.3	all	Coordination breakdown	Misaligned positioning actions	Poor alignment between robot positioning and human preparation	Incorrect setup or rework	4	2	4	32
I5	A.3 → A.4	all	Resource conflict	Improper handover	Lack of synchronization or unclear transfer condition	Instability or interference	5	2	4	40
I6	A.4-A.8	H1, H2	Coordination breakdown	Unsynchronized execution	Lack of coordination or pacing mismatch between operators	Inconsistent assembly sequence	4	3	4	48
I6	A.4-A.8	H1, H2	Goal misalignment	Incorrect task objective	Misinterpretation of assembly goal	Defective assembly outcome	4	2	5	40
I7	B.1 → B.2	all	Temporal misalignment	Incorrect activation timing	Delay in human input or unclear triggering signal	Delayed robot operation	3	3	3	27
I8	B.2 → B.3	all	Coordination breakdown	Unsynchronized transition	Missing coordination between robot completion and human action	Execution inconsistency	3	2	4	24
I9	B.3-B.7	H1, H2	Coordination breakdown	Lack of synchronization	Independent pacing and lack of shared timing cues	Variable execution quality	3	3	4	36
I10	B.8	H1, H2	Asymmetric awareness	Incomplete alignment	Lack of explicit communication before next step	Incorrect readiness	3	2	4	24
I11	B.9 → B.10	all	Asymmetric awareness	Missing confirmation	Weak or non-salient feedback from system	Incorrect system state interpretation	3	2	5	30
I12	C.1	R1, R2	Coordination breakdown	Misaligned positioning	Poor coordination between robots or calibration issues	Incorrect component placement	4	2	4	32
I13	C.1 → C.2	all	Resource conflict	Incorrect positioning	Misalignment between robot output and human expectation	Assembly interference	5	2	4	40
I14	C.2-C.3	H1, H2	Role ambiguity	Unclear responsibility	Lack of role definition or shared ownership	Delayed or missing actions	3	2	6	36

Based on the RPN values, the most critical execution-level failures in the dyadic FMECA are insufficient torque application during tightening operations (RPN = 72) and missing grommet insertion (RPN = 64). These results indicate that the dyadic analysis mainly prioritizes local execution reliability, including tightening quality, component sequencing, handling stability, and local human-robot handover conditions. Most failures indeed originate from human procedural mistakes or from inaccuracies in robotic manipulation and handling.

Importantly, these failure modes remain valid in more complex MH-MR configurations. Execution-level errors such as incorrect assembly sequences, insufficient torque, or component misalignment may still occur locally within a multi-agent system.

However, in MH-MR contexts, these failures are no longer confined to isolated interactions. Instead, they may propagate across multiple agents and interact with additional coordination, communication, and coherence constraints. To clarify the additional coverage provided by the coherence-driven analysis, Table 15 compares the main failure mechanisms identified by the dyadic FMECA and by the proposed MH-MR framework. By analogy process failure mode for 1H-1R are grouped by failure mode categories.

The comparison shows that conventional dyadic FMECA mainly covers execution-level failure mode categories, while the coherence-driven MH-MR analysis makes explicit additional interaction-level failure mode categories related to synchronization, shared information, role allocation, workspace compatibility, and process-state alignment. Therefore, the proposed framework should be interpreted as an extension of conventional FMECA rather than as a replacement.

Table 14
FMECA for dyadic (1H-1R) skateboard collaborative assembly.

Elementary task	Agents involved	Process Failure Mode	Cause(s)	Effect(s)	S	O	D	RPN
A.4	H	Bolt inserted upside down	Human error; lack of visual guide	Assembly defect; disassembly required	4	4	2	32
A.5	H	Missing grommet in sequence	Distraction or part skipped	Poor performance; rework	4	4	4	64
A.5	H	Grommets and protectors assembled in wrong order	Human forgets step order; unclear visual hierarchy	Assembly defect; disassembly required	4	2	4	32
A.8/B.4/B.7/C.3	H	Nut falls before threading begins	Unstable grip; inattentive handling	Nut lost; rework or component search	2	4	2	16
A.8/B.4/B.7/C.3	H	Insufficient torque applied	Under-tightening due to fatigue or distraction	Loosening under load; safety risk	6	2	6	72
A.3/B.2/B.5/C.1	R	Misaligned part presentation	Poor calibration, difficulties in picking phase	Human struggles to assemble; process delay; risk of dropping	4	2	4	32
A.3/B.2/B.5/C.1	R	Gripper slippage during hand-over	Inadequate grip force estimation or sensor error	Part falls or bounces; risk of damage or safety incident	6	2	4	48
A.4/A.5/A.6/A.7/A.8	H-R	Baseplate slips from gripper due to excessive force by human	Human applies force before verifying robot release or stable grasp	Part drop, rework needed, delay	6	2	4	48

Table 15
Comparison between dyadic FMECA and coherence-driven MH-MR framework ("Yes" indicates that the failure type is explicitly identified by the method; "No" indicates that it is not identified; "Partially identified" indicates that it may be indirectly captured only through its local execution-level manifestation or through its effect on interaction-level coherence).

Failure mechanism	Representative example in the case study	Dyadic FMECA	Coherence-driven MH-MR framework
Human procedural error	Bolt inserted upside down; missing grommet; wrong assembly order; nut falls; insufficient torque applied	Yes	No
Robot handling or presentation error	Misaligned part presentation; gripper slippage	Yes	Partially identified
Local human-robot handling mismatch	Baseplate slips due to excessive force by human	Yes	Partially identified
Temporal misalignment	Delayed or incorrect input triggering robot action	Partially identified	Yes
Asymmetric awareness	Missing readiness signal or missing confirmation feedback	No	Yes
Coordination breakdown	Unsynchronized human-human execution or robot-human transition	Partially identified	Yes
Resource conflict	Instability or interference during handover/ positioning	Partially identified	Yes
Goal misalignment	Misaligned task objective during truck assembly	No	Yes
Role ambiguity	Unclear responsibility during joint assembly	No	Yes

6. Discussion

The results obtained through the coherence-driven MH-MR design framework highlight a clear distinction between execution-level and interaction-level failure mechanisms in collaborative manufacturing processes.

The dyadic FMECA analysis shows that a wide range of process failures can be effectively identified by focusing on individual tasks and agent actions. These include human procedural errors, improper force application, incorrect assembly sequences, and inaccuracies in robotic manipulation.

However, the MH-MR analysis reveals an additional class of failures that cannot be captured with traditional approaches. As a result, failures emerge from misalignments in coordination, communication, and collaboration, rather than from isolated execution errors. The coherence-driven framework proposed in this work enables the identification of these interaction-level failures by explicitly identifying failure mode categories such as coordination breakdown, asymmetric awareness, role ambiguity, and goal misalignment. It should be noted that the proposed coherence dimensions are not intended to attribute human-like cognition or intentionality to robots since they describe observable misalignments among human decisions, programmed robot actions, control signals, operational states, and task responsibilities.

From a practical standpoint, the proposed framework offers significant advantages for the design and engineering of MH-MR systems. Unlike traditional approaches, which are often applied after process definition, the coherence-driven method can be used proactively during process design. In particular, it enables:

- the identification of critical interaction points where misalignment may occur;
- the explicit definition of alignment requirements across agents;
- the anticipation of potential failure conditions before process execution;
- the integration of interaction-level considerations into task allocation and workstation design.

Beyond a single application, the framework also supports an iterative design process. Starting from an initial process configuration, engineers can apply the methodology to identify interaction-related vulnerabilities, revise the process accordingly for example by modifying task allocation, introducing additional communication mechanisms, or redefining coordination strategies and repeat the analysis. This iterative loop enables the progressive refinement of the system, reducing the likelihood of coherence violations and improving the overall process robustness (see Fig. 6).

The proposed framework should also be distinguished from control-logic verification and system-level safety analysis methods. However,

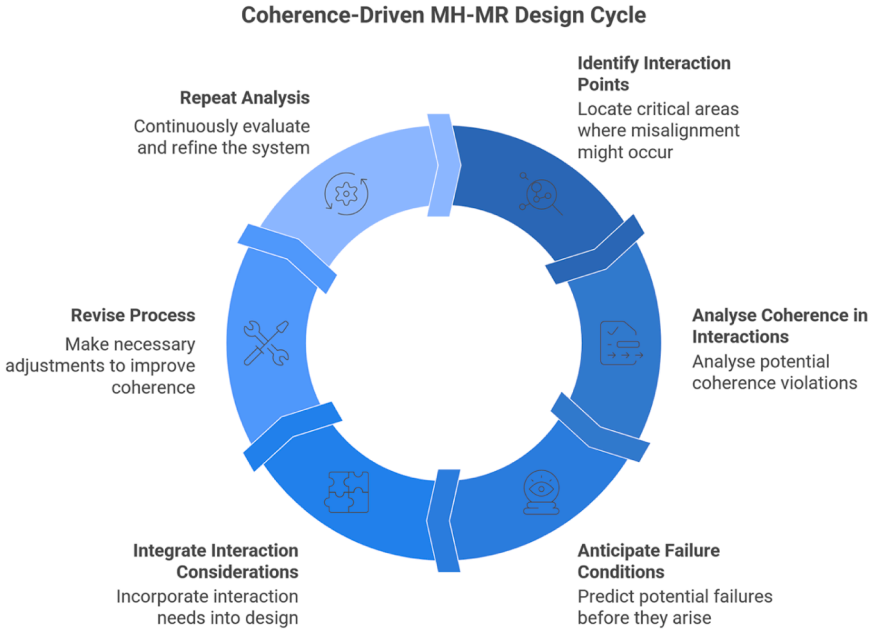


Fig. 6. Coherence-Driven design Cycle for MH-MR processes.

the objective of the coherence-driven framework is different. It does not verify deterministic robot behaviour or replace interlock design; instead, it provides an early-stage process-design layer for identifying which interactions are vulnerable to misalignment and why. The resulting coherence violations can therefore be used as inputs for defining control requirements, interface feedback, synchronization mechanisms, or subsequent analyses. Moreover, the framework goes beyond spatial, temporal, and information-related misalignments by also considering cognitive and goal-related coherence requirements, such as human interpretation of process state, role clarity, task objectives, and process priorities. These aspects are generally not explicitly represented in conventional task-level FMECA but become relevant in MH-MR systems where process robustness depends on the alignment of multiple interacting agents. In industrial environments, this approach can support the design of collaborative assembly processes by guiding decisions related to synchronization strategies, communication interfaces, role definition, and workspace organization, acting as a continuous improvement mechanism for MH-MR process design.

7. Conclusions

This paper presented a coherence-driven framework for the design and analysis of multi-human multi-robot (MH-MR) systems, shifting the focus from task-level failure analysis to interaction-based process analysis. The proposed methodology enables the identification of failure mechanisms as the result of coherence violations across agents, providing a structured approach to analyse how interactions influence process quality.

The application to a skateboard assembly case study shows how the framework can systematically derive interactions, identify critical coherence requirements, and anticipate potential failure conditions. In this context, the comparison with conventional FMECA highlighted that execution-level failures alone are not sufficient to describe the behaviour of MH-MR systems, as additional failure mechanisms emerge from coordination, communication, and collaboration among agents.

Despite these contributions, some limitations must be acknowledged. First, the proposed methodology relies on qualitative assessment, particularly in the identification of coherence requirements and violations. Second, the two case-specific indicators introduced in Section 5.2.4 provide support for interpreting temporal and spatial coherence requirements, but they do not directly measure the degree of coherence or the occurrence of coherence violations. Third, the case study is limited to a controlled laboratory scenario and should therefore be interpreted as a demonstrative application rather than as a full industrial validation. While it captures basic MH-MR interaction mechanisms, it does not fully represent the variability, scale, and uncertainty of complex industrial environments.

These limitations point to several directions for future research. A first development concerns the definition and validation of more general quantitative or semi-quantitative coherence indicators, considering, for example, deviations from synchronization requirements, spatial compatibility constraints, and information consistency. Such indicators could support a more objective evaluation of coherence violations and comparison of different MH-MR configurations. A second direction is the integration of the framework with simulation environments to support process design. Additionally, further work is required to validate the methodology in industrial settings, considering larger-scale systems and more complex interaction structures.

Finally, future research may explore the extension of the framework toward real-time monitoring of coherence during operation, enabling the detection of interaction-level misalignments as they occur. This would further strengthen the link between process design and operational control, supporting the development of more adaptive and resilient MH-MR systems. The present contribution should therefore be interpreted as a foundational qualitative framework; increasing its objectivity and computability through quantitative coherence metrics, simulation-based assessment, and validation on larger industrial cases represents the next research step.

Ethics approval

The authors respect the ethical guidelines of the journal.

Consent for publication

Not applicable.

CRediT authorship contribution statement

Matteo Capponi: Writing – original draft, Validation, Methodology, Conceptualization. **Aurora Sofia Di Matteo:** Validation, Methodology, Formal analysis. **Luca Mastrogiacomo:** Supervision, Methodology, Conceptualization. **Fiorenzo Franceschini:** Validation, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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