Quality Challenges in Multi-Human Multi-Robot Collaborative Assembly Design: A Coherence-Based Methodology to Analyse Process Failures

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Paulo Sampaio - Conference Chair

School of Engineering, Systems and Production Department

Campus Gualtar, 4710-057 Braga, Portugal
http://icqem.dps.uminho.pt/
icqem@dps.uminho.pt


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## FOREWORD

It is our great pleasure to welcome you to Lisbon, Portugal, and to NOVA University Lisbon, the venue of the seventh edition of the International Conference on Quality Engineering and Management (ICQEM). Since its inception, ICQEM has established itself as a distinguished forum for the dissemination of research, the exchange of ideas, and the advancement of knowledge in the fields of quality engineering and quality management.

The 7th International Conference on Quality Engineering and Management (ICQEM26) brings together scholars, practitioners, and industry leaders to explore the evolving role of quality in engineering, management, and organizational systems. Building on the success of previous editions, this year's conference will broaden its scope to address how quality principles can be applied to the growing complexity of technological, organizational, and societal challenges.

Quality engineering and quality management are no longer confined to traditional manufacturing or service environments — they represent critical disciplines for navigating uncertainty, driving innovation, and ensuring resilience in a rapidly changing world. By adopting a systems perspective, the 7th ICQEM seeks to highlight how quality can serve as the connective framework across diverse fields such as digital transformation, healthcare, sustainability, supply chain management, and organizational design.

The conference will provide a unique interdisciplinary platform for sharing research insights, practical experiences, and forward-looking strategies. Participants will engage in discussions on emerging methodologies, integration of advanced technologies, and the role of leadership in fostering a culture of excellence. With a focus on both rigorous academic contributions and real-world impact, ICQEM26 emphasizes the power of quality to bridge disciplines and tackle complex engineering and management challenges.

At the 7th ICQEM, our aim is to not only advance the theory and practice of quality but also to reaffirm its broader mission: building systems that are effective, efficient, sustainable, and human-centered.

NOVA University, July 2, 2026.
Sincerely,

**Conference Local Chair**
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**Conference Chair**
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7th International Conference on Quality Engineering and Management

*2-3 July 2026, Universidade NOVA de Lisboa, Lisbon, Portugal*

# Quality Challenges in Multi-Human Multi-Robot Collaborative Assembly Design: A Coherence-Based Methodology to Analyse Process Failures

**Matteo Capponi[1], Aurora Sofia di Matteo[2], Luca Mastrogiacomo[3], Fiorenzo Franceschini[4]**

1 Politecnico di Torino, Italy - Dipartimento di Ingegneria Gestionale e della Produzione (DIGEP); matteo.capponi@polito.it
2 Politecnico di Torino, Italy - Dipartimento di Ingegneria Gestionale e della Produzione (DIGEP); aurora.dimatteo@polito.it
3 Politecnico di Torino, Italy - Dipartimento di Ingegneria Gestionale e della Produzione (DIGEP); luca.mastrogiacomo@polito.it
4 Politecnico di Torino, Italy - Dipartimento di Ingegneria Gestionale e della Produzione (DIGEP); fiorenzo.franceschini@polito.it

***Abstract-*** **As collaborative robotics in manufacturing evolves from single-human single-robot (1H-1R) collaboration to multi-human multi-robot (MH-MR) teams, interaction complexity increases significantly. Although the traditional Failure Mode, Effects and Criticality Analysis (FMECA) tool is widely adopted in quality engineering, in collaborative manufacturing processes it is primarily structured around 1H-1R interactions. This makes it less effective at capturing failure modes that emerge from multi-agent dynamics. This paper therefore proposes an exploratory coherence-based methodology for analysing and evaluating failure modes in MH-MR collaborative assembly processes. The methodology is inspired by the "3Cs" model which identifies Collaboration, Coordination and Communication as critical aspects for effective teamwork. A case-study regarding the collaborative assembly of a skateboard involving two human operators and two cobots is then presented. This highlights how timing misalignments, ambiguous feedback, role ambiguity and spatial interference can affect process and product quality when multiple agents operate in parallel within a shared workspace. The proposed framework provides process designers with a structured tool supporting the development of more robust, human-aware collaborative manufacturing processes in MH-MR systems.**

**Keywords: Multi-Human Multi-Robot Collaboration, Process Quality, Assembly, FMECA, Manufacturing, Process Failure**

## I. INTRODUCTION

Manufacturing systems are undergoing a critical change, driven by the shift from Industry 4.0 to Industry 5.0. The latter emphasises flexibility, resilience and human-centred production [1]. This transition is also reflected in European policy perspectives on Industry 5.0, which frame future manufacturing around human-centricity, sustainability and resilience [2]. In this context, collaborative robotics plays a central role, enabling humans and robots to work closely together and perform manufacturing tasks jointly. Initial industrial applications of human-robot collaboration (HRC) have primarily centred on dyadic configurations, typically comprising one human operator and one collaborative robot operating within a shared workspace [3], [4]. From a quality and reliability perspective, one-human-one-robot (1H-1R) systems have been widely investigated. Previous studies have identified common causes of process failures in collaborative assembly [5], [6]. Well-established quality tools, such as Failure Mode, Effects and Criticality Analysis (FMECA), have been successfully adopted to structure and prioritise these risks. Recent technological advances are enabling a shift towards more complex collaborative configurations characterised by the simultaneous presence of multiple human operators and multiple robots working together on shared assembly tasks, also called "MH-MR" teams. The authors adopt the following definition of a MH-MR team: *"a Multi-Human Multi-Robot (MH-MR) team is a structured group composed of at least three 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"* [7]. Multi-human-multi-robot (MH-MR) teams offer significant potential benefits in terms of flexibility, scalability and workload distribution, particularly in complex, low-volume assembly environments [7], [8], [9]. However, the increased number of interacting agents introduces new dynamics relating to coordination, communication, shared situational awareness and decision-making, substantially increasing system complexity. These dynamics concern both physical collaborations, involving shared workspace occupation, object handling and task execution, and cognitive collaboration, involving decision-making, mutual adaptation, shared awareness and interpretation of system states. The interdependencies between multiple humans and robots result in emergent behaviours at the team level, where disturbances affecting one agent can spread throughout the system. From a quality engineering perspective, this raises important questions about the nature of process errors and failure modes in MH-MR assembly. Failures relating to miscoordination, conflicting task priorities, ineffective communication or loss of shared awareness may not immediately present as safety issues but can significantly impact product quality and operational performance through delays, rework or assembly errors. While the literature covers topics related to one human one robot collaboration [3], [5], [10], there is a lack of systematic classifications of process failure modes tailored to MH-MR collaborative assembly. This paper addresses this gap by proposing an exploratory coherence-based methodology to identify failure modes that are specific to collaborative assembly carried out by teams composed of both humans and robots. Based on existing analyses of failures in 1H-1R collaborative assembly [5], the proposed taxonomy broadens the scope of analysis to include new categories of failures relating to coordination, communication and decision-making at the team level. This exploratory and conceptual contribution aims to frame the problem and provide a structured foundation for future empirical validation and methodological developments. The paper is organised as follows. Section 2 reviews the relevant literature on failure analysis in human-robot collaboration and MH-MR manufacturing systems. Section 3 introduces a conceptual methodology to analyse process failure modes in MH-MR teams while Section 4 presents a case-study on the collaborative assembly of a skateboard. Section 5 and 6 respectively present and discuss the main results while Section 7 summarises the main conclusions, limitations, and future developments.

## II. Related work

Over the past decade, human-robot collaboration (HRC) in manufacturing, particularly for assembly tasks, has been explored as a means of combining human flexibility with robotic precision [1], [11], [12], [13], [14]. Effective task structuring and coordination are critical for supporting reliable collaboration between humans and robots and exploiting their respective strengths [15], [16], [17]. In recent years, researchers developed comprehensive ways to evaluate the performance of HRC systems. Gervasi et al. [11] addressed this issue by defining multiple "HRC dimensions" and proposing an integrated framework with which to compare different collaboration configurations. In practice, the evaluation of an HRC system usually involves considering metrics such as productivity, team efficiency and ergonomics/operator workload. The concept of "fluency" in HRC has also been introduced to capture how smoothly a human-robot team works as a unit [18]. Recent literature surveys have compiled a wide range of performance indicators and benchmarking tasks for collaborative robots in manufacturing [7], [9]. Overall, the state of the art shows that HRC systems can achieve improved safety and efficiency over manual processes when evaluated on both productivity and human factors [13], [19], [20]. The introduction of HRC to the factory floor brings benefits, as well as novel process failure modes and quality challenges. Coronado et al. [21] evaluated quality in human-robot interaction ("HRI") by providing an overview of factors used to evaluate performance and human well-being quality aspects in HRI applications. Similarly, Verna et al. [22] proposed a novel tool to evaluate manufacturing quality in human-robot collaboration combining the analysis of product defects variant with the evaluation of human well-being. Kokotinis et al. [10] also proposed a novel quality index to assess several aspects of human-robot collaboration, including quality, in production contexts. While these studies focus on quality as a broad and multidimensional concept, a more detailed understanding requires considering how quality is affected by errors and failures occurring during collaboration. Humans and robots working together may misinterpret mutual actions or signals, which can lead to misaligned efforts or even collisions. Such miscoordination can result in assembly errors or quality defects that would not occur in a purely manual or automated process [5]. Antonelli and Stadnicka [23] observe that HRC in assembly can lead to different types of process failures, which are not seen in manual assembly or fully robotic cells, due to the novel interactions between humans and robots. Hence, ensuring process quality in HRC requires addressing new error modes, ranging from human errors (e.g. a worker positioning a part incorrectly for the robot) and robot errors (e.g. misdetections or improper force application) to interface issues (e.g. miscommunication of intentions). Haggy et al. [24] investigated a combination of Bow-Tie Analysis and FMEA for assessing HRC safety. By integrating the two techniques, the authors evaluated a collaborative assembly case study. However, most HRC research to date assumes a dyadic interaction. The upcoming Industry 5.0 brings scenarios in which multiple humans and multiple robots (see Figure 1) collaborate in semi-structured environments [1]. Transitioning from dyadic (i.e., one-to-one) collaboration to team-like configurations has great potential, offering higher flexibility, adaptability and productivity by dynamically allocating human and robotic resources where they are needed. For instance, in a complex assembly process, two robots could assist a pair of human workers on different subtasks simultaneously, or hand parts between each other and the humans [7]. Nourmohammadi et al. [25] have already demonstrated the benefits of this approach: they developed a model for balancing an assembly line that allows for multiple operators (both human and cobot) at the same station. They also showed that enabling such parallel human-robot collaboration can significantly improve line productivity. Despite these early successes, scaling up to MH-MR teams introduces new challenges that largely remain unresolved. As Capponi et al. [7] observe, the manufacturing field is focusing attention to more complex configurations of multi-human multi-robot team, and traditional 1H-1R evaluation models may no longer be adequate. In this regard, Ma et al. [8] showed that the traditional metrics of human-robot interaction (HRI) for performance and efficiency must be expanded to incorporate teamwork metrics, including cognitive and environmental aspects of teamwork. Similarly, Riedelbauch et al. [9] developed a holistic set of metrics and evaluation methods to assess human robot teams, including dimensions such as productivity, safety, flexibility, job quality, etc. Another crucial aspect in designing processes involving multiple agents, is to ensure that the right number of robots assist at the right time, humans are neither overloaded nor idle, and that safety is maintained. Scalability is therefore recognised as a major challenge in human-robot teaming research [26]. Furthermore, aspects such as communication protocols and situational awareness are of critical importance in MH-MR settings: robots must not only communicate with humans, but also with each other while keeping humans informed [27]. Additionally, multiple humans may require new interfaces to manage robot teams collectively. In terms of process quality, maintaining high quality and reliability may become more difficult when more agents are involved. For example, new process failure modes could occur when two robots collaborate on a task (e.g. synchronisation failures between robots), or when multiple humans divide their attention among several robots. Capponi et al. [7] emphasised that integrating multiple humans and robots introduces new challenges such as governing interactions within the team, communication means, and human behaviour. This paper addresses this gap by building on three complementary fields of literature: failure analysis in dyadic HRC, teamwork-oriented evaluation of human-robot teams, and quality-oriented assessment of collaborative manufacturing. These contributions are extended toward a coherence-based analysis of process failures in MH-MR collaborative assembly.

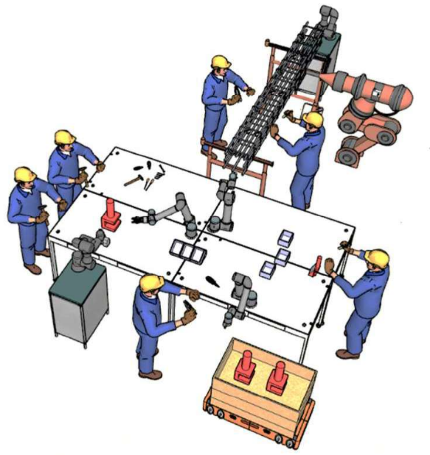

Fig. 1. Multi-human multi-robot team in a general manufacturing scenario

## III. Methodology

From a methodological perspective, this work adopts an exploratory conceptual modelling approach supported by expert-based assessment. To capture emergent process failures in MH-MR teams, the authors adopted a teamwork-oriented perspective based on the "3Cs" model introduced by Ma et al [8], which identifies collaboration, coordination, and communication as the three core dimensions that govern effective teamwork:

- Collaboration: Ensuring that team members share common goals, intentions and plans, and work together towards them. This involves building and maintaining shared mental models among humans and robots. In practice, collaboration means that all parties understand the joint objectives aligning their efforts for mutual success [28].
- Coordination: Ensuring that the interdependent tasks and resources of a team are managed so that the actions of its members are synchronised. In teams comprising both humans and robots, there are inherent informational and physical dependencies between members, thus activities must be carefully sequenced and synchronised to avoid conflict [29]
- Communication: The exchange of information necessary to enable coordination and collaboration over time. As the team works, critical data, status updates and intentions must be transmitted and understood by the agents involved. This encompasses verbal or written messages, signals, cues and interface feedback between humans and robots [30].

In dyadic systems, risks are often confined to the interaction between a single operator and a robot, and failure analysis tends to focus on task- or agent-specific issues. In multi-human multi-robot teams agents involved collaborate and coordinate to successfully perform a task. In this study, the authors hypothesised that the performance of MH-MR teams emerges from maintaining coherence conditions across the process. Coherence refers to the consistent alignment of system components, agent behaviours and shared information necessary for the successful execution of collaborative tasks. Accordingly, a process failure mode can be defined as a violation of a coherence condition necessary for accomplishing a collective task. Based on this assumption, a structured methodology is proposed to guide designers in identifying process failure modes for MH-MR-oriented FMECA. The methodology is composed of three main phases: (i) MH-MR characterisation; (ii) Coherence requirement analysis and (iii) Failure mode derivation.

### *A. Phase 1: MH-MR characterisation*

A MH-MR team can be characterised across six macro-dimensions:

- **Team composition** defined as the structural configuration of agents (i.e., number of humans and robots, types, etc.)
- **Task allocation** refers to the distribution of operational activities among agents
- **Agent responsibilities** regard the clarity of the authority and of the decision-making mechanisms
- **Coordination** defined as the synchronization of interdependent tasks and resources
- **Collaboration** defined as the sharing of common goals, intentions and plans
- **Communication** understood as the exchange of information enabling coordination and collaboration over time

These macro-dimensions define the areas in which coherence must be preserved and in which misalignments may structurally emerge.

### *B. Phase 2: Coherence requirement analysis*

For each macro-dimension, the designer identifies the conditions required for successful task performance. The analysis focuses on multiple coherence features, including:

- **Goal coherence**: alignment between the objectives of individual agents and the overall system goals.
- **Information coherence**: consistency of shared data and representation of the system state.
- **Temporal coherence**: synchronisation of actions and decision timing.
- **Spatial coherence**: compatibility of physical workspace occupation and movement.
- **Cognitive coherence**: shared situational awareness among agents.

Each macro-dimension requires a specific combination of these coherence features. This phase makes explicit the alignment conditions that must be satisfied during operation.

### *C. Phase 3: Failure mode derivation*

Failure modes are systematically derived as violations of the coherence requirements identified in Phase 2. For each macro-dimension and associated coherence features, the designer evaluates: how partial or complete misalignment may occur and how they can propagate across agents and the whole system. The derived failure modes are then organized within a FMECA framework. Each process failure mode is documented using the standard FMECA schema [31]:

- **Process Failure Mode**: A deviation from expected performance within a task or interaction involving one or more agents.
- **Causes**: The specific factors that lead to the occurrence of the failure mode. Causes may be technical (e.g., sensing error), procedural (e.g., misaligned task sequence), or cognitive (e.g., incorrect assumption), and can originate from either human or robot behaviour or their interaction.
- **Effects**: The observable consequences of the failure on task execution, process fluency, product integrity, or team behaviour.
- **Responsible Agents**: Human, Robot, or Joint thus indicating the agent primarily associated with the origin of the failure.

In addition to the standard qualitative descriptions, each failure mode is assigned a Severity (S), Occurrence (O), and Detection (D) rating according to a 1-10 ordinal scale. Severity reflects the impact of the process failure on safety, product integrity, or process continuity (1 = negligible effect; 10 = safety-critical or system-disrupting effect). Occurrence estimates the likelihood of the failure under nominal operating conditions (1 = rare; 10 = frequent). Detection represents the probability that the failure will be identified before leading to significant consequences (1 = easily detectable; 10 = difficult to detect). The industrial case study presented in the following section illustrates the application of the proposed methodology to a specific assembly scenario.

## IV. CASE-STUDY: MH-MR COLLABORATIVE ASSEMBLY OF A SKATEBOARD

To support the conceptual development of the proposed methodology, this paper presents a case study of the collaborative assembly of a skateboard (see Figure 2) performed by a multi-human, multi-robot (MH-MR) team.


Fig. 2. (a) Parts of a skateboard and (b) the assembled product

This scenario was designed and executed in a laboratory environment (Mind4Lab, Politecnico di Torino, Italy). Assembly took place on a dedicated workstation equipped with two collaborative robots (Universal Robots UR3e), as shown in Figure 3. The robotic agents were integrated into the workspace to operate in physical proximity with the human operators. The operational team was composed of two human operators and two robotic agents. Each human-robot pair worked on one side of the table, assembling their respective portion of the skateboard in parallel. The two sub-teams performed equivalent tasks simultaneously, requiring coordination during the process for the use of shared resources and process alignment. In this configuration, the robotic agents mainly performed predefined physical support actions, such as part positioning and tool presentation, while human operators retained most cognitive and adaptive functions, including decision-making, verification, timing adaptation, mutual coordination, alignment and joining. This parallel execution modality was selected to reproduce realistic industrial dynamics and maximise inter-agent interaction phenomena.

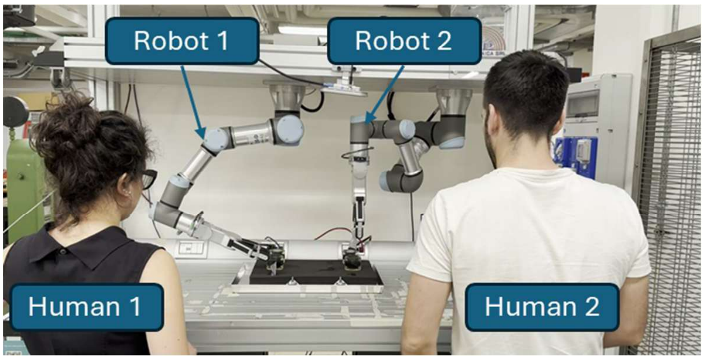


Fig. 3. The assembly work area with two collaborative robots UR3 (Robot 1 and Robot 2) and two human operators (Human 1 and Human 2)

The product to assemble was a standard skateboard comprising three main subsystems: trucks, the board, and the wheels. The process was divided into three macro-phases (see Figure 4): (i) Truck assembly; (ii) Trucks on the board assembly and (iii) Wheels and trucks assembly. The detail steps of the assembly process are provided in Table 1.

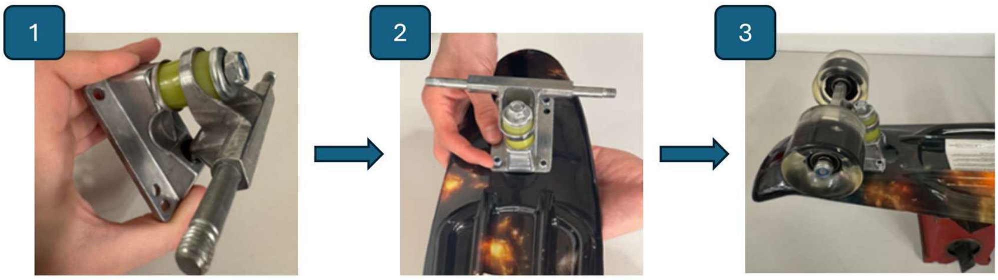


Fig. 4. The three phases of the assembly of the skateboard: (1) truck assembly; (2) trucks on the board assembly (3) wheels and trucks assembly.

Task allocation followed a symmetric model: each human-robot pair was responsible for half portion of the product (front and rear). Table 1 summarises the elementary steps within each macro-phase. While the robotic agents' assignments were predefined, the human operators had some flexibility in their decision-making, particularly with regard to mutual adaptation and action timing.

TABLE I. LIST OF THE ELEMENTARY STEPS NECESSARY TO ASSEMBLE THE SKATEBOARD AND THE RELATED ALLOCATION TO THE AGENT INVOLVED (H1:HUMAN 1, H2: HUMAN 2; R1:ROBOT 1 AND R2:ROBOT 2)

| Assembly phase | Detailed steps | Agent involved |
| --- | --- | --- |
| A) Assembly of the truck (x2) | A.1 Communicate and align on action | H1/H2 |
| | A.2 Send input to cobot | H1/H2 |
| | A.3 Pick and place the baseplate (BP) | R1/R2 |
| | A.4 Insert the bolt (BL1) into the baseplate (BP), ensuring that the threaded part of the bolt is facing upwards. | H1/H2 |
| | A.5 Insert the larger metal protector (LMP) and then the larger yellow grommet (LYG) onto the bolt (BL1). | H1/H2 |
| | A.6 Insert the black pin cup (PC) on the hanger (HNG) and on the baseplate (BP). | H1/H2 |
| | A.7 Insert the smallest yellow grommet (SYG) and then the smallest metal protector (SMP) onto the bolt (BL1). | H1/H2 |
| | A.8 Screw the nut (N1) onto the bolt, pushing the head of the bolt while tightening and the truck is assembled. | H1/H2 |
| | B.1 Send input to cobot | H1/H2 |

| | | |
|---|---|---|
| B) Assembly of the wheels on the truck (x2) | B.2 Pick and place wheel (WL) | R1/R2 |
| | B.3 Mount the wheel on the hanger | H1/H2 |
| | B.4 Insert the washer (W) and tighten with a nut (N3). | H1/H2 |
| | B.5 Pick and place the wheel | R1/R2 |
| | B.6 Mount the wheel on the hanger. | H1/H2 |
| | B.7 Insert the washer (W) and tighten with a nut (N3). | H1/H2 |
| | B.8 Communicate and align on action | H1/H2 |
| | B.9 Send input to cobot | H1/H2 |
| | B.10 Verify input received from both humans | R1/R2 |
| C) Assembly of the truck on the board | C.1 Take the board (B) and put its underside upwards on the specific supports so that the tips of the board (B) protrude from the supports. | R1/R2 |
| | C.2 Put the truck on the board, making sure that the holes in the baseplate (BP) match those in the board (B). (x2) | H1/H2 |
| | C.3 Insert the bolts (BL2) into the four holes, tighten them with the nuts (N2) to join the truck and the board. (x2) | H1/H2 |

In this configuration, the two operators work in parallel within a shared workspace, performing either symmetrical or complementary actions on mirrored components simultaneously. Explicit interaction between humans occurs at specific stages, particularly when initiating robot actions (e.g. steps A.1 and B.8). At these times, synchronisation and confirmation of readiness are necessary to trigger robot operation. Beyond these explicit interaction points, however, the process involves continuous implicit mutual adjustments between humans. The operators regulate their pace, spatial positioning and manipulation strategies based on their peripheral awareness of each other's actions. These micro-adjustments are not formally described in the task sequence and cannot be fully predicted at the planning stage since they emerge from shared situational awareness and real-time adaptation within the common workspace.

## V. Results

Process failure analysis conducted through the extended FMECA framework highlights conventional and emergent failure modes in collaborative assembly involving multi-human multi-robot teams. A series of structured focus groups involving a panel of domain experts was used to identify MH-MR-specific failure modes. The panel was composed of engineers and academic researchers expert in process quality management, human-robot collaboration and collaborative robotics system design. All participants had prior experience of industrial assembly systems. The focus group sessions were conducted using the methodology proposed in this study. The discussion was specifically structured according to the MH-MR macro-domains and the corresponding coherence features identified in section 3. Failure modes were derived by systematically examining potential violations of goal, temporal, spatial, informational and cognitive coherence within the defined MH-MR configuration.

This analysis led to the development of two distinct FMECA tables. The first one (Table 2) addresses the dyadic (1H-1R) configuration and represents an extension of the framework proposed by Maisano et al. [32]. In this table, each process failure mode is associated with the corresponding assembly step, potential causes, effects, responsible agent, and the assigned Severity (S), Occurrence (O), and Detection (D) ratings. The second table (Table 3) concerns the MH-MR configuration. In addition to the conventional FMECA elements (assembly step, failure mode, causes, effects, responsible agent, and S-O-D scores), this extended table includes two additional columns: the MH-MR macro-dimension involved, and the specific coherence feature violated. The S-O-D values were determined through expert judgement during the focus group sessions, based on the participants' experience. It is important to note that failure modes identified in the dyadic configuration remain conceptually valid within MH-MR systems. Execution-level errors such as incorrect assembly sequences, insufficient torque, or component misalignment may still occur locally within a multi-agent team. However, in MH-MR contexts these process failures may propagate differently, interacting with additional agents and coherence constraints. The MH-MR FMECA therefore extends the dyadic analysis. Compared with the dyadic configuration, the MH-MR analysis does not replace execution-level failure modes, but adds failure modes emerging from team-level interaction dynamics, such as temporal desynchronisation, spatial interference, ambiguous feedback, loss of shared situational awareness and unclear task ownership.

TABLE II. FMECA TABLE FOR THE 1H-1R COLLABORATIVE ASSEMBLY OF THE SKATEBOARD

| Assembly step | Process Failure Mode | Cause(s) | Effect(s) | Responsible | S | O | D |
|---|---|---|---|---|---|---|---|
| A.4 | Bolt inserted upside down | Human error; lack of visual guide | Assembly defect; disassembly required | Human | 6 | 6 | 4 |
| A.5 | Missing grommet in sequence | Distraction or part skipped | Poor performance; rework | Human | 6 | 6 | 6 |
| A.5 | Grommets and protectors assembled in wrong order | Human forgets step order; unclear visual hierarchy | Assembly defect; disassembly required | Human | 6 | 4 | 6 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| A.8/B.4/B.7/ C.4 | Nut falls before threading begins | Unstable grip; inattentive handling | Nut lost; rework or component search | Human | 4 | 6 | 4 |
| A.8/B.4/B.7/ C.4 | Insufficient torque applied | Under-tightening due to fatigue or distraction | Loosening under load; safety risk | Human | 10 | 4 | 8 |
| A.3/B.2/B.5/ C.1 | Misaligned part presentation | Poor calibration, difficulties in picking phase | Human struggles to assembly; process delay; risk of dropping | Robot | 6 | 4 | 6 |
| A.3/B.2/B.5/ C.1 | Gripper slippage during hand-over | Inadequate grip force estimation or sensor error | Part falls or bounces; risk of damage or safety incident | Robot | 8 | 4 | 6 |
| A.4/A.5/A.6/ A.7/A.8 | 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 | Joint | 8 | 4 | 6 |

The 1H-1R FMECA highlights process failure modes primarily associated with execution-level errors occurring within single human-robot interactions. Most process failures originate from human procedural mistakes or from robot-related handling inaccuracies. In this configuration, failures are typically localised and directly attributable to a specific agent. The Severity (S), Occurrence (O), and Detection (D) ratings reflect this execution-focused nature. For example, insufficient torque application exhibits the highest Severity (S = 10) due to potential safety implications under load, combined with relatively high Detection difficulty (D = 8), since under-tightening may not be immediately visible. In contrast, failures such as a nut falling before threading begins show lower Severity (S = 4) and high detectability (D = 4), as the issue is immediately observable and correctable.

On the other hand, the MH-MR FMECA reveals that many critical process failures in MH-MR systems are not caused by individual agents' actions, but by breakdowns in coordination, communication and collaboration within the team. Coordination failures in MH-MR systems are primarily caused by violations of temporal and spatial coherence. Since multi-agent execution requires procedural coupling, even minor desynchronisation can propagate throughout the system. For instance, if one human agent fails to confirm readiness or input signals are not provided in a timely manner, temporal coherence is disrupted, resulting in execution delays and process uncertainty. Similarly, uncoordinated spatial actions, such as lifting or placing components without confirming their position, represent violations of spatial coherence and can potentially escalate into safety-relevant events (e.g. S = 8). While the agents may function correctly in isolation, the absence of shared timing and spatial awareness mechanisms can negatively affect the process.

Communication-related process failures correspond to violations of information coherence. Ambiguous robot confirmation signals or missed human inputs are not technological malfunctions per se, but rather breakdowns in communicative alignment. When feedback is weak or non-salient, humans may misinterpret the system state, and this misalignment may remain undetected until a subsequent action fails (often reflected in higher detection scores). Regarding collaboration, situations in which one human moves a component without verifying their teammates' readiness indicate a loss of shared situational awareness and reflect a coherence violation rather than an isolated error. Hence, failures associated with collaboration extend beyond the exchange of information and encompass goals, cognition and authority. For example, role ambiguity can lead to situations in which neither person takes action because ownership of the task is unclear. In this case, the issue relates to cognitive coherence, since the agents do not share the same understanding of task ownership, and although the severity may be moderate, the absence of action can be difficult to detect promptly.

Overall, the MH-MR FMECA shows that multi-agent process failure modes are best understood as structured coherence violations across coordination, communication, collaboration, and related structural domains.

TABLE III. FMECA TABLE FOR MH-MR COLLABORATIVE ASSEMBLY OF THE SKATEBOARD

| **Assembly step** | **Failure Mode** | **Cause(s)** | **Effect(s)** | **Responsible** | **MH-MR macro-dimension** | **Violated coherence dimension** | **S** | **O** | **D** |
|---|---|---|---|---|---|---|---|---|---|
| A.2/B.1/B.9 | One human forgets to press input | Distraction or misunderstanding of readiness | Task halted; unnecessary delay | Human | Coordination | Temporal coherence | 4 | 6 | 4 |
| A.4/A.5/A.6/ A.7/A.8 | Inputs not given in timely succession | Desynchronized press due to lack of prompt | Execution delay; human uncertainty | Joint | Coordination | Temporal coherence | 4 | 6 | 6 |
| C.1 | Uncoordinated lifting or placement | No shared cue or tactile handoff | Board misalignment or drop | Human | Coordination | Goal coherence | 8 | 4 | 8 |
| B.9 | Robot provides weak or ambiguous confirmation | Non-salient feedback channel | Human confused about process state | Robot | Communication | Information coherence | 4 | 6 | 8 |
| C.2 | Humans interfere during precision tasks | Physical proximity; overlapping intent | Micro-delays or safety stops | Human | Team structure | Spatial coherence | 6 | 6 | 6 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| A.2/B.1/B.9 | Robots do not receive human input | Latency or wrong channel used | No action triggered | Human | Communication | Information coherence | 4 | 4 | 8 |
| A.3/B.2/B.5/ C.1 | Robot enters safety mode due to collision | Humans enter robot space unexpectedly | Process interruption; requires restart or reset | Human | Team structure | Spatial coherence | 8 | 4 | 6 |
| C.2 | Human moves board without checking teammate's status | Lack of mutual monitoring; absence of shared visual cues | Collision or misalignment | Human | Collaboration | Cognitive coherence | 8 | 4 | 8 |
| C.2 | Neither human acts due to unclear responsibility | Role ambiguity; absence of explicit leadership in task | Task skipped or delayed; passive blocking | Human | Agent responsibilities | Cognitive coherence | 6 | 4 | 10 |

## VI. Discussion

The proposed coherence-based extension of FMECA complements previous work on failure analysis in dyadic human-robot assembly by shifting the focus from isolated task execution to interaction-level misalignments within MH-MR teams. While prior studies on HRC failures mainly address human errors, robot handling inaccuracies or interface-related issues within one-to-one collaboration [5], [23], the present analysis shows that additional failure modes emerge when several agents operate in parallel and share physical, informational and cognitive dependencies. This finding is consistent with teamwork-oriented perspectives on human-robot teams, which argue that performance evaluation should include coordination, communication and shared awareness dimensions beyond conventional productivity or safety indicators [8], [9]. From a process design perspective, the results suggest that MH-MR failure analysis should not only verify whether each agent can perform its assigned task, but also whether the team can preserve temporal, spatial, information, goal and cognitive coherence throughout the process. Accordingly, the proposed approach should be interpreted as a conceptual design-support tool rather than as a fully validated predictive model. Its main value lies in making multi-agent dependencies explicit and in helping designers anticipate failure modes that may remain hidden in conventional dyadic FMECA analyses.

## VII. Conclusions

This study proposes an exploratory coherence-based methodology for analysing and evaluating process failure modes in multi-human, multi-robot collaborative assembly systems, by extending the traditional Failure Mode Effects and Criticality Analysis (FMECA). Applying the approach to a collaborative assembly scenario involving two human operators and two cobots shows its practical relevance. The analysis highlights that process failures in MH-MR systems are often not attributable to isolated agent limitations, but to breakdowns in shared coherence conditions within parallel and shared activities. By explicitly linking failure modes to MH-MR analytical macro-dimensions, the proposed methodology helps process designers to systematically anticipate multi-agent risks during the design of collaborative manufacturing systems. The main outputs produced by the methodology are the MH-MR characterisation structure, the taxonomy of coherence features and the extended FMECA schema linking failure modes to team-level dimensions and coherence violations.

However, the present work remains exploratory in nature. The identification, classification, and evaluation of failure modes are derived from a specific assembly scenario. Consequently, the resulting taxonomy should be adapted for different industrial contexts. The assigned severity, occurrence and detection ratings are qualitative and based on expert judgement rather than large-scale empirical data. Furthermore, the case study represents a controlled collaborative setting with limited variability in task structure, environmental constraints, and operator heterogeneity. Real industrial environments may introduce additional sources of uncertainty, such as varying levels of operator expertise, or unstructured workspace conditions. These factors could generate further classes of process failure mode that are not captured in the current analysis.

Therefore, future research should aim to validate and refine the proposed methodology by applying it to multiple industrial case studies and thus extending the taxonomy beyond the specific assembly process examined here. Particular attention should be given to collecting empirical performance data to support a more quantitative evaluation of S-O-D ratings. Overall, this work should be viewed as an initial step towards establishing a structured process failure analysis framework for MH-MR systems, providing a conceptual and methodological basis for further empirical development.

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