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Applying C-MAS plug and Produce Control to Automated Coffee Bag Re-work Under Variability.

Precious Ehis Oyemolan

UNIVERSITY WEST

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Date:	June 6, 2026
Author:	Precious Ehis Oyemolan
Examiner:	Mahmood Khabbazi
Advisor:	Basssm Massouh
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Summary

This thesis investigates the application of a C-MAS combined with plug-and-produce principles for automating coffee bag rework processes in highly variable manufacturing environments. Traditional rework operations in food packaging are largely manual because deformable coffee bags vary in size, seal type, fill condition, and internal mass distribution, making them difficult for conventional robotic systems to handle. Existing centralized automation architectures are typically rigid and optimized for repetitive production flows, limiting their ability to adapt to changing conditions and mixed product inputs.

To address these challenges, the thesis proposes a decentralized control architecture based on C-MAS. In the proposed system, coffee bags are modelled as part agents carrying production goals, while machines are modelled as resource agents providing capabilities such as opening, emptying, refilling, and sealing. Instead of relying on predefined sequences, the system uses runtime goal-capability matching, where part agents dynamically request services and resource agents respond according to their capabilities and operational constraints.

The research follows a conceptual engineering case study methodology consisting of three phases: use-case definition, C-MAS modelling, and scenario development. Key variability factors such as bag size, seal type, fill condition, mixed sequencing, and resource unavailability are incorporated into structured test scenarios to evaluate system adaptability and robustness.

The proposed architecture is organized into four layers: agent layer, coordination layer, execution layer, and validation layer. This structure supports modularity, scalability, and decentralized decision-making. The findings indicate that the C-MAS approach improves flexibility, resource utilization, and fault tolerance compared with conventional centralized systems. It also enables plug-and-produce functionality, allowing resources to be added or removed with minimal reconfiguration effort.

The thesis concludes that C-MAS provides a promising solution for adaptive manufacturing systems aligned with Industry 4.0 principles. Future work includes industrial implementation, integration of industrial communication protocols, and KPI-driven optimization for enhanced real-time performance and autonomous decision-making.

Affirmation

This master's degree report, ***A**pplying C-MAS Plug and Produce Control to Automated Coffee Bag Rework Under Variability* was written as part of the master's degree work needed to obtain a Master of Science with specialization in Robotics degree at University West. All material in this report, that is not my own, is clearly identified and used in an appropriate and correct way. The main part of the work included in this degree project has not previously been published or used for obtaining another degree.

Precious Ehis Oyemolan 12-09-2026

Signature by the author Date

Precious Ehis Oyemolan

Contents

Preface

SUMMARY **3**

AFFIRMATION **4**

CONTENTS **5**

SYMBOLS AND GLOSSARY **7**

Main Chapters

1 INTRODUCTION **8**

1.1 Background 8
1.2 Aim and Objectives 9
1.3 Research Questions 9

2 LITERATURE **10**

2.1 Rework Operations in Packaging Systems 10
2.2 Reconfigurable and Modular Manufacturing 10
2.3 Multi-Agent Systems in Manufacturing 11
2.4 The C-MAS Approach 12
2.5 Research Gap 12

3 METHOD **13**

3.1 Phase 1 Re-work used case definition 13
3.1.1 Process scope *13*
3.1.2 Variability definition *14*
3.2 Phase 2 C-MAS modelling 15
3.2.1 Part Agent Representation *15*
3.2.2 Resource Agent Representation *16*
3.2.3 Distributed Coordination *16*
3.3 Phase 3 Scenario and Test Matrix Development 17

4 SYSTEM DESIGN AND ARCHITECTURE **20**

4.1 Overview of the C-MAS Architecture 20
4.2 Agent Types and Responsibilities 21
4.2.1 Part Agents *22*
4.2.2 Resource Agents *22*
4.3 Communication Layer 23
4.4 Execution Layer 24
4.5 Validation and Evaluation 24
4.6 Architectural Characteristics 25

5 RESULTS AND DISCUSSION **26**

5.1 Experimental Execution Results 26
5.2 Validation of the C-MAS Coordination Logic 27
5.3 Discussion of System Behaviour 27

5.4 Limitations of the Current Implementation 28
5.5 Summary of Results 28
6 CONCLUSION AND FUTURE WORK 29
6.1 Conclusion 29
6.2 Answers to the Research Questions 30
6.3 Future Work 30
6.3.1 Real-World Implementation 30
6.3.2 Integration of Key Performance Indicators (KPIs) 31
6.4 Final Remarks 31
7 REFERENCES 32

Symbols and glossary

C-MAS	Configurable Multi-Agent System. A decentralized manufacturing control architecture in which autonomous agents dynamically coordinate production tasks based on capabilities and goals.
KPI	Key Performance Indicator. Quantitative metrics used to evaluate manufacturing performance, efficiency, and system responsiveness.
MAS	Multi-Agent System. A distributed computational system composed of multiple interacting autonomous agents capable of communication and decision-making.
MQTT	Message Queuing Telemetry Transport. A lightweight communication protocol commonly used for industrial IoT and real-time machine communication.
OPC UA	Open Platform Communications Unified Architecture. An industrial communication protocol that enables secure and standardized data exchange between automation devices and software systems.
RMS	Reconfigurable Manufacturing System. A manufacturing paradigm designed to rapidly adjust production functionality and capacity in response to changing demands.
WIP	Work-In-Progress. Products or materials currently undergoing processing within the manufacturing system.

1 Introduction

1.1 Background

Industrial rework processes in food production remain largely manual, particularly when handling deformable packaging such as coffee bags filled with beans or powder. These packages exhibit: Variable geometry, shifting internal mass distribution, nonlinear deformation under grasp, sensitivity to tearing during cutting.

Conventional robotic bin picking systems are predominantly optimized for rigid objects within structured environments, rendering the automation of deformable packaging rework a significant technical challenge [1], [2]. This limitation is compounded by traditional automation architectures, which rely on centralized and hard coded control logic designed for predefined and repetitive sequences. While such approaches perform effectively under stable production conditions, they lack the flexibility required to accommodate increasing variability [3]. In contrast, modern manufacturing systems are expected to manage high product diversity while maintaining efficiency and robustness, a key paradigm within Industry 4.0 [4], [5]. In packaging environments, variability arises from differences in product formats, materials, and defect conditions, with rework operations presenting an even greater challenge due to the need to process non-standard, defective, or mixed inputs. For example, automated coffee packaging rework cells must handle bags with varying sizes, seal types, and fill states, significantly increasing system complexity and necessitating more adaptive and decentralized control strategies.

Despite advancements in automation and Industry 4.0 technologies, a gap remains in the development of control architectures capable of combining flexibility, scalability, and real-time adaptability for such variable rework scenarios. Existing systems often struggle to support dynamic reconfiguration or seamless integration of new resources without significant downtime or reprogramming effort [6]. This highlights the need for decentralized and modular control approaches that can inherently manage variability and enable plug-and-produce functionality.

Recent advances in robotic manipulation research have highlighted a growing interest in the handling of deformable objects, addressing limitations associated with conventional rigid object automation [7]. In parallel, Industry 4.0 paradigms emphasize the transition toward modular, distributed, and reconfigurable production systems capable of adapting to dynamic manufacturing environments. Within this context, Configurable Multi-Agent Systems (C-MAS) emerge as a promising approach, as they enable decentralized decision making and support plug-and-produce capabilities, thereby providing a flexible and scalable foundation for advanced industrial automation [8].

This thesis addresses the gap between manual rework and limited, rigid automation, and the requirement for flexible and adaptive automated rework processes for deformable objects under variability [9].

This challenge aligns with broader industrial developments toward modular and reconfigurable manufacturing. The thesis will adapt plug-and-produce and C-MAS as key enablers of the proposed solution.

The C-MAS, developed and demonstrated at University West, represents a distributed control approach aligned with plug-and-produce principles.

C-MAS models a production system using three fundamental abstractions:

Parts: entities that carry a production goal.
Resources: equipment modules that provide defined capabilities.
Instead of executing a rigid, centrally programmed sequence, the system dynamically coordinates actions based on goal capability matching. This reduces dependency on static sequencing logic and supports adaptation to changes in format, availability, or configuration.
In this thesis, coffee bags undergoing rework are modelled as "part agents" with defined target outcomes (e.g., repacked and resealed), while rework equipment modules are modelled as "resource agents" advertising capabilities such as opening, emptying, refilling, and sealing.

1.2 Aim and Objectives

The aim of this thesis is to provide a solution formulized around the C-MAS plug-and-produce control and apply to automated coffee bag rework cell operating under variability. To achieve this aim, the following objectives are defined:

- To analyse the challenges associated with variability in automated coffee bag rework, including product, process, and system-level uncertainties.
- To design a C-MAS-based control architecture that enables decentralized decision-making for rework operations.
- To implement plug-and-produce functionality, allowing seamless integration and removal of resources without requiring system reprogramming or downtime.
- To model the rework system and its variability using a suitable simulation or experimental platform.

1.3 Research Questions

- How can C-MAS plug-and-produce be implemented to enable flexible reconfiguration in an automated coffee bag rework system?
- What control strategies are required to handle shape and mass variability in granular filled packaging?

2 Literature

This section reviews existing literature relevant to the development of flexible and adaptive packaging systems, with a particular focus on rework operations and reconfigurable manufacturing approaches. Prior research has explored various strategies to address increasing production variability, including advances in automation architectures, modular system design, and distributed control paradigms. By examining these contributions, this section aims to identify key trends, technological enablers, and existing limitations, thereby establishing the foundation for the research gaps addressed in this study.

2.1 Rework Operations in Packaging Systems

Rework operations play an important role in modern packaging systems by enabling the recovery of value from defective, damaged, or opened packages while reducing production waste [10]. In contrast to primary packaging lines, rework systems frequently process different and unpredictable inputs, including mixed product types, partially processed packages, and items with different defect types. This results in higher operational uncertainty and increased format variation within the production environment.

Traditional packaging automation is typically based on sequence driven control architecture designed for highly standardized production flows. These systems perform efficiently when processing homogenous product streams with predictable process steps. However, when variability increases due to product defects, machine disturbances, or mixed product batches, these systems often require manual intervention, system reconfiguration, or temporary bypassing of automated processes [11]. The mismatch between increasing production variability and rigid automation architecture has motivated research into more flexible and adaptive control paradigms capable of dynamically handling changing production conditions.

Rework operations introduce both significant opportunities and notable challenges within modern packaging systems. They enable improved resource efficiency, cost savings, and sustainability by recovering value from defective or non-conforming products. The reviewed literature highlights strong potential for enhancing system performance through more flexible and adaptive approaches, particularly in environments characterized by high variability and uncertainty.

On the other hand, the inherent complexity of rework processes such as handling mixed product flows, varying defect types, and unpredictable inputs poses substantial challenges for conventional automation systems. Sequence-driven control architectures remain limited in their ability to respond dynamically, often leading to increased reliance on manual intervention and reduced overall system efficiency. Furthermore, existing research tends to focus on isolated solutions, with limited integration across system levels and a lack of standardized frameworks for implementation.

2.2 Reconfigurable and Modular Manufacturing

Reconfigurable Manufacturing Systems (RMS) have been proposed as an approach to address the need for flexibility in modern production environments. RMS architecture

aims to enable rapid adjustment of manufacturing capacity and functionality in response to changing product requirements and production volumes [5], [12], [13].
Key principles of RMS include Modularity, allowing systems to be constructed from interchangeable modules. Integrability, enabling new components to be integrated quickly into existing systems. Customization capability, supporting product specific configurations. Scalability, allowing the system to expand or contract depending on production demand.
An advance realization of the RMS concept is the plug-and-produce paradigm, which focuses on reducing engineering effort when integrating new equipment into production systems. In plug-and-produce architecture, production modules can automatically identify themselves, describe their capabilities, and become operational within the system with minimal manual configuration [14], [15], [16]. Rather than relying on rigid, pre-programmed sequences, plug-and-produce approaches emphasize capability-based modelling, where machines expose services that can be dynamically orchestrated to perform production tasks. This approach supports flexible production environments where equipment configurations may change frequently. Research on modular production systems consistently highlights the importance of distributed control architectures and standardized communication interfaces for achieving effective plug-and-produce functionality [4], [17].
Reconfigurable and modular manufacturing systems offer substantial opportunities for improving flexibility and responsiveness in modern production, as highlighted in the literature through principles such as modularity, integrability, scalability, and customization, along with the plug-and-produce paradigm that reduces engineering effort and enables dynamic system reconfiguration via capability-based models. These approaches support faster adaptation to changing product demands and more efficient system evolution. However, important challenges remain, including the lack of universally adopted standards for communication and interoperability, difficulties in integrating heterogeneous equipment, and increased system complexity associated with distributed control architectures. Additionally, much of the existing research is still conceptual or limited to small-scale implementations, with insufficient validation in real industrial settings. Consequently, further work is needed to bridge the gap between theory and practice while addressing issues related to standardization, robustness, and large-scale deployment.

2.3 Multi-Agent Systems in Manufacturing

Multi-Agent Systems (MAS) represent a distributed control paradigm in which manufacturing entities are modelled as autonomous software agents capable of communication, negotiation, and decision making [18]. In industrial applications, agents may represent machines, transport systems, production resources, and individual products [19]. MAS-based control architectures have been explored in several manufacturing contexts, including dynamic production scheduling, adaptive product routing, fault detection and recovery, distributed resource allocation.
Compared with traditional centralized control systems, MAS architecture offers several advantages. These include improved system scalability, reduced single points of failure, and enhanced responsiveness to local disturbances. Despite these advantages, industrial adoption of MAS in manufacturing has been limited by challenges related to system modelling, validation, integration with existing automation infrastructure, and ensuring deterministic system behavior [20].

2.4 The C-MAS Approach

The C-MAS architecture, developed at University West, represents an effort to operationalize MAS concepts within a structured and configurable plug-and-produce framework. C-MAS introduces a modelling approach that separates production goals from the capabilities of physical resources. In this architecture, part agents represent production objectives or product requirements, resource agents represent machine capabilities/skills which describe the operations that resources can perform.

The designed negotiation between agents allows production tasks to be dynamically matched with available resource capabilities at runtime, rather than being predefined through fixed control sequences. Key characteristics of the C-MAS architecture include:

- Explicit separation between part goals and resource capabilities
- Reduced reliance on hard-coded sequential control logic
- System configuration through structured modelling instead of extensive programming

Previous experimental implementations have demonstrated that C-MAS can support flexible production systems with modular equipment configurations [21], [22]. However, structured documentation of its application in packaging rework scenarios under defined variability conditions remains limited.

2.5 Research Gap

The existing literature provides strong theoretical support for the use of plug-and-produce architecture and multi-agent systems in flexible manufacturing environments. Nevertheless, several limitations remain in current research.

First, relatively few studies present clearly bounded industrial use cases that demonstrate the practical implementation of these concepts in real production scenarios.

Second, many studies do not explicitly define or categorize the variability dimensions present in the production environment.

Third, evaluations of flexible manufacturing architectures often lack quantitative performance metrics or KPI driven analysis.

Furthermore, limited work exists that provides application ready modelling frameworks capable of supporting direct industrial deployment.

To address these limitations, this thesis develops a structured case study focusing on automated coffee bag rework under production variability. The study applies the C-MAS plug-and-produce control architecture to evaluate how distributed capability-based control can improve system flexibility, reduce engineering effort, and support adaptive handling of defective products in packaging processes.

3 Method

This study follows a conceptual engineering case study methodology to develop and evaluate a control architecture based on C-MAS for automated coffee bag rework. The goal is to design a system capable of handling variability in defective products while enabling plug-and-produce functionality, allowing rapid integration of new equipment or processes without extensive reprogramming. The research is design oriented and consists of three phases:

- Use case definition
- CMAS modelling
- Scenario construction

3.1 Phase 1 Re-work used case definition

3.1.1 Process scope

The rework cell is defined at a conceptual level as a sequential transformation process: faulty coffee bags are identified and routed into the system, after which they undergo a series of controlled operation opening, emptying, refilling, and resealing before being reintroduced into the production flow. This high-level representation deliberately abstracts away mechanical and hardware specific details to emphasize the underlying control architecture and coordination logic governing the system.

From a systems perspective, the process can be interpreted as a discrete event workflow in which each stage constitutes a distinct operational state with clearly defined inputs, outputs, and transition conditions. The initial stage involves the detection and handling of defective units, which may be identified through upstream quality control mechanisms. Once introduced into the rework cell, each bag is subjected to an opening operation that enables access to its contents. This is followed by the emptying phase, during which the original contents are removed in a controlled manner to prevent contamination or loss.

Subsequently, the refilling stage ensures that the bag is replenished with the correct quantity and quality of coffee, adhering to production specifications.

Finally, the resealing operation restores the bag to a condition suitable for distribution, ensuring both structural integrity and product preservation. Each of these stages must be carefully coordinated to maintain process efficiency, avoid bottlenecks, and ensure consistent quality outcomes.

By abstracting the mechanical implementation, the focus shifts toward the design of supervisory control strategies, synchronization between process steps, and fault handling mechanisms. This includes considerations such as state transitions, interlocks, timing constraints, and communication between subsystems. Such an approach enables a more flexible and scalable system design, facilitating future modifications or integration with broader manufacturing execution systems without being constrained by specific hardware configurations.

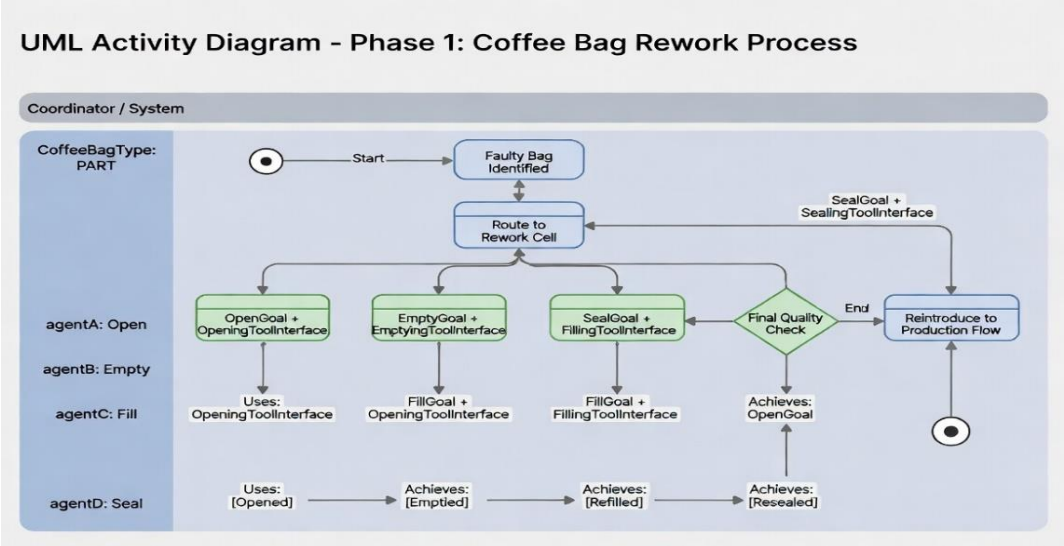


Figure 1. Part agents dynamically request services according to their current processing goals, while resource agents evaluate requests based on capabilities, availability, and constraints. Task allocation emerges through decentralized negotiation, resource selection, execution feedback, and dynamic reconfiguration when resources become unavailable.

3.1.2 Variability definition

To ensure robustness and adaptability of the rework cell, key sources of process variability are explicitly defined and incorporated into the system model. Variability in this context refers to the range of differences in input characteristics and operating conditions that the system must be capable of handling without compromising performance, quality, or reliability.

One primary dimension of variability is bag size, typically categorized into discrete classes such as small, medium, and large. Differences in size influence handling requirements, gripping strategies, opening mechanisms, and fill volumes, thereby affecting both control logic and timing parameters. Closely related is the seal type, which may vary depending on packaging specifications (e.g., heat-sealed, zip-lock, or adhesive seals). Each seal type imposes distinct constraints on the opening and resealing operations, requiring adaptive control strategies and potentially different process paths.

Another critical dimension is the fill condition of incoming bags. Bags may arrive empty, partially filled, or contaminated, each condition necessitating different handling procedures. For example, partially filled bags require accurate detection and controlled emptying, while contaminated bags may trigger additional rejection or cleaning protocols. This variability introduces conditional branching in the control logic and increases the complexity of state transitions within the system.

In addition to individual bag characteristics, mixed input sequencing represents a higher-level variability dimension. Rather than processing homogeneous batches, the system must handle sequences of bags with differing attributes in an arbitrary or non-deterministic order. This requires the control architecture to dynamically adapt between successive operations without manual reconfiguration, emphasizing the need for flexible scheduling, real-time decision-making, and robust synchronization mechanisms.
Together, these variability dimensions form the foundation for systematic scenario testing. By constructing test cases that combine different variable states, the system can be evaluated under a wide spectrum of operating conditions. This approach supports the validation of control logic, identification of edge cases, and assessment of system performance, ultimately contributing to a more resilient and scalable rework cell design.

3.2 Phase 2 C-MAS modelling

3.2.1 Part Agent Representation

Within the proposed control architecture, each coffee bag is modelled as an autonomous part agent, encapsulating both its physical properties and its process related information. This abstraction enables decentralized decision-making and facilitates dynamic coordination within the rework cell. By representing each bag as an individual agent, the system can more effectively manage variability, track progress, and adapt to changing process conditions in real time.
Each part agent is defined by a set of core attributes that describe its objectives and status throughout the rework process. First, the target outcome specifies the desired end condition of the bag, typically defined as successfully repacked and resealed in accordance with quality standards. This goal-oriented representation allows the control system to evaluate whether the required sequence of operations has been completed and to determine if additional actions are necessary.
Second, the current state attribute captures the real-time status of the bag within the process workflow. This may include states such as “unprocessed,” “opened,” “emptied,” “refilled,” or “sealed,” corresponding to the sequential stages of the rework cell. The state information is continuously updated as the bag progresses through the system and serves as a key input for decision-making, task allocation, and synchronization between process units.
Third, the part agent includes format attributes, which describe the physical and qualitative characteristics of the bag. These may encompass properties such as size, seal type, material composition, and fill condition. Such attributes directly influence how the bag is handled and processed, enabling the control system to tailor operations to the specific requirements of each unit.
By integrating these elements, the part agent representation provides a structured and extensible framework for managing individual items within the rework cell. It supports traceability, enhances flexibility in handling heterogeneous inputs, and enables more sophisticated control strategies, such as condition-based routing and adaptive process planning. This agent-based modelling approach is particularly well-suited for complex, variable production environments where centralized control alone may be insufficient to ensure efficiency and robustness.

3.2.2 Resource Agent Representation

In the proposed architecture, equipment modules within the rework cell are modelled as resource agents, each encapsulating a set of parameterized capabilities that define the operations it can perform. This abstraction enables a modular and flexible system design, where processing tasks are dynamically allocated based on resource availability, capability matching, and current system conditions.

Each resource agent is characterized by a portfolio of capabilities, which correspond to the fundamental operations required in the rework process. These include functions such as opening, emptying, filling, and sealing. Importantly, these capabilities are not defined as fixed, monolithic actions, but rather as parameterized services that can be adapted to different process requirements. For instance, an opening capability may support multiple opening types depending on seal characteristics, while a filling capability may operate within a specified volume range to accommodate different bag sizes.

The parameterization of capabilities allows resource agents to handle a range of input variations without requiring explicit reconfiguration. For example, a sealing module may support different seal types, such as heat sealing or adhesive closure, with parameters specifying temperature, pressure, or duration. Similarly, an emptying module may adjust its operation based on the initial fill condition of the bag. This flexible representation is essential for managing the variability inherent in the rework process.

In addition to capabilities, each resource agent incorporates capability constraints, which define the operational limits and conditions under which a given function can be executed. These constraints may include physical limitations (e.g., maximum and minimum bag sizes), process constraints (e.g., allowable fill volumes or compatible seal types), and performance related factors (e.g., cycle time, throughput, or energy consumption). By explicitly modelling these constraints, the system can ensure that only feasible and valid task resource assignments are made.

The interaction between part agents and resource agents is governed by a capability-matching mechanism, where the requirements of a part agent are aligned with the available capabilities of resource agents. This enables dynamic task allocation, supports decentralized decision-making, and enhances the overall adaptability of the system.

Furthermore, the explicit representation of constraints contributes to more robust operation by preventing infeasible process configurations and enabling early detection of potential conflicts or bottlenecks.

Overall, the resource agent representation provides a structured and extensible framework for modelling equipment within the rework cell. It supports modularity, scalability, and flexibility, which are critical for handling diverse processing requirements and evolving production conditions.

3.2.3 Distributed Coordination

Coordination within the rework cell is realized through a distributed, agent-based mechanism grounded in runtime goal capability matching. In contrast to traditional control approaches that rely on fixed sequencing and predefined workflows, the proposed system enables dynamic interaction between part agents and resource agents. This shift allows the system to respond more effectively to variability, disturbances, and changing operational conditions.

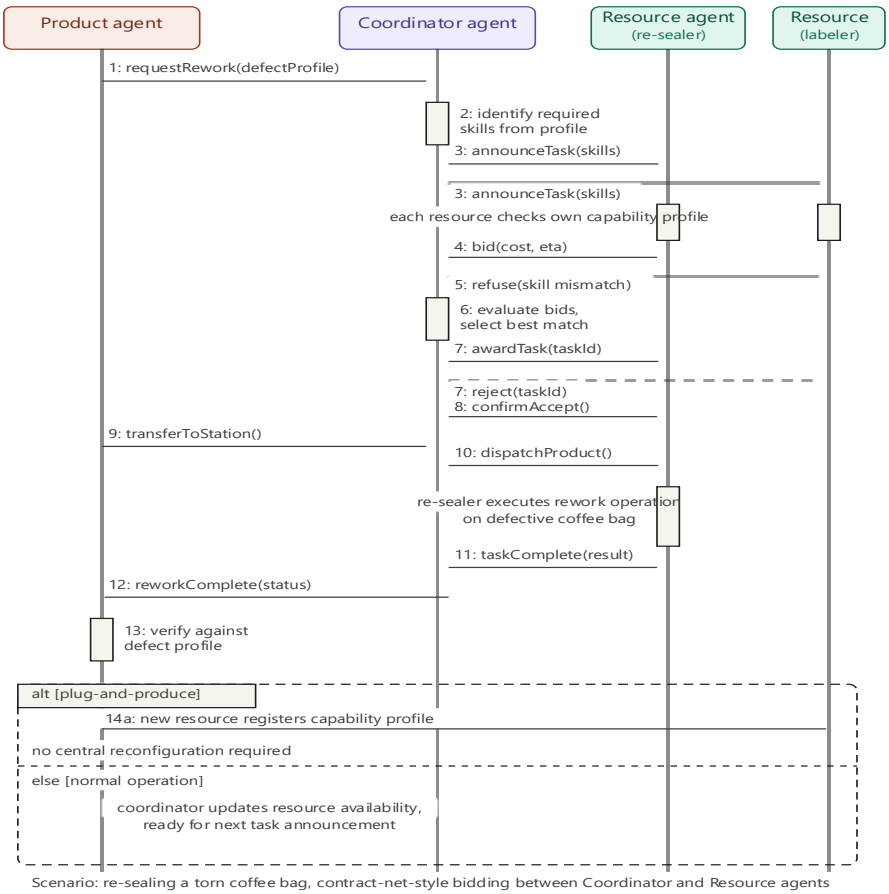
At the core of this coordination paradigm is the principle that part agents actively request services based on their current state and target outcome. Rather than passively following a predetermined sequence of operations, each part agent evaluates its processing requirements and generates service requests that align with its immediate goals.

For example, a bag in an opened state may request an emptying service, while a refilled bag may seek a compatible sealing operation. This goal-driven behaviour ensures that process progression is both context-aware and adaptive.
In parallel, resource agents respond to incoming requests according to their available capabilities and current operational status. Each resource agent evaluates whether it can fulfil a given request by considering both its parameterized capabilities and its constraints, such as capacity limits, current workload, or compatibility with the requested operation. If multiple resource agents can perform the same task, selection mechanisms such as priority rules, load balancing strategies, or optimization criteria can be applied to determine the most suitable allocation.
This interaction establishes a decentralized coordination structure in which task allocation emerges dynamically from the continuous negotiation between part agents and resource agents. As a result, the system does not depend on rigid process plans but instead adapts in real time to variations in input characteristics, resource availability, and process conditions. For instance, if a particular module becomes unavailable or overloaded, part agents can redirect their requests to alternative resources without requiring global reconfiguration.
The distributed nature of this coordination approach enhances system robustness and scalability. It reduces single points of failure, supports parallelism, and enables incremental system expansion by introducing additional resource agents without fundamentally altering the control logic. Moreover, it facilitates the handling of mixed input sequencing and heterogeneous processing requirements, as each part agent independently navigates the process based on its specific needs.
Overall, runtime goal capability matching provides a flexible and resilient coordination mechanism that aligns with the demands of modern, variable production environments. It enables adaptive task allocation, improves resource utilization, and supports the efficient handling of diverse and dynamically changing process scenarios.

3.3 Phase 3 Scenario and Test Matrix Development

In Phase 3, a structured set of scenarios is developed to systematically evaluate the behaviour and robustness of the rework cell under varying operational conditions. The purpose of this phase is to ensure that the proposed control architecture is not only functionally correct under nominal conditions, but also resilient to variability, disturbances, and dynamic changes in the production environment.
The scenario set is designed to capture representative and challenging situations that the system may encounter in practice. One key category includes mixed bag formats, where bags of different sizes, seal types, and fill conditions are introduced in non-uniform sequences. This type of scenario tests the system's ability to handle heterogeneity and to dynamically adapt task allocation without relying on batch processing assumptions.
Another important category involves sudden format changes, where the characteristics of incoming bags shift abruptly during operation. Such changes may include transitions between bag sizes or sealing requirements, requiring the system to rapidly reconfigure its processing strategy. These scenarios are particularly relevant for assessing the responsiveness and flexibility of the distributed coordination mechanism, as well as the effectiveness of runtime goal capability matching.

In addition, the scenario set incorporates resource unavailability cases, representing situations in which one or more resource agents become temporarily or permanently unavailable due to faults, maintenance, or capacity limitations. These scenarios are critical for evaluating system robustness, as they test the ability of part agents to reroute requests and of the overall system to maintain operational continuity despite disruptions.
To support a comprehensive and systematic evaluation, a test matrix is constructed by combining the defined variability dimensions. This matrix specifies different permutations of factors such as bag size, seal type, fill condition, input sequencing, and resource availability. By organizing test cases in this structured manner, it becomes possible to ensure coverage of both typical and edge-case conditions, while avoiding redundant or arbitrary testing.
The use of a test matrix also facilitates reproducibility and traceability in the evaluation process. Each test case can be explicitly defined, executed, and analysed, allowing for consistent comparison of system performance across different scenarios. Furthermore, this approach supports the identification of performance bottlenecks, failure modes, and potential improvements in the control strategy.
Overall, Phase 3 establishes a rigorous foundation for validating the proposed system. By combining structured scenario design with a systematic test matrix, it enables a thorough assessment of adaptability, robustness, and scalability in the presence of real-world variability.



Scenario: re-sealing a torn coffee bag, contract-net-style bidding between Coordinator and Resource agents

Figure 2. Sequence diagram of a contract-net-style bidding protocol for rework task allocation, illustrated for re-sealing a torn coffee bag. The product agent requests rework; the coordinator agent identifies required skills and announces the task to resource agents, which bid or refuse based on capability match. The coordinator evaluates bids, awards the task to the best match, and dispatches the product for execution. After the resource agent completes the rework and reports back, the product agent verifies the result against the defect profile. The final alternative block shows the system's plug-and-produce capability: new resources can register their capability profiles without central reconfiguration, while under normal operation the coordinator simply updates resource availability for the next

4 System Design and Architecture

4.1 Overview of the C-MAS Architecture

The proposed C-MAS is designed to support a flexible and adaptive coffee bag rework process in a highly variable manufacturing environment. The architecture follows a decentralized paradigm in which decision-making is distributed among autonomous agents rather than controlled by a central authority.

The system is structured into four interrelated layers: the agent layer, the coordination layer, the execution layer, and validation. This layered design enables a clear separation of concerns between decision-making, communication, and physical process execution. At a high level, part agents representing coffee bags initiate service requests based on their current state and desired target outcome. These requests are communicated through the coordination layer, where resource agents evaluate their ability to perform the requested operations. Once a suitable match is identified, tasks are executed in the physical system, and feedback is provided to update the system state.

This architecture supports modularity, scalability, and adaptability, making it particularly suitable for manufacturing systems characterized by dynamic conditions and product variability.

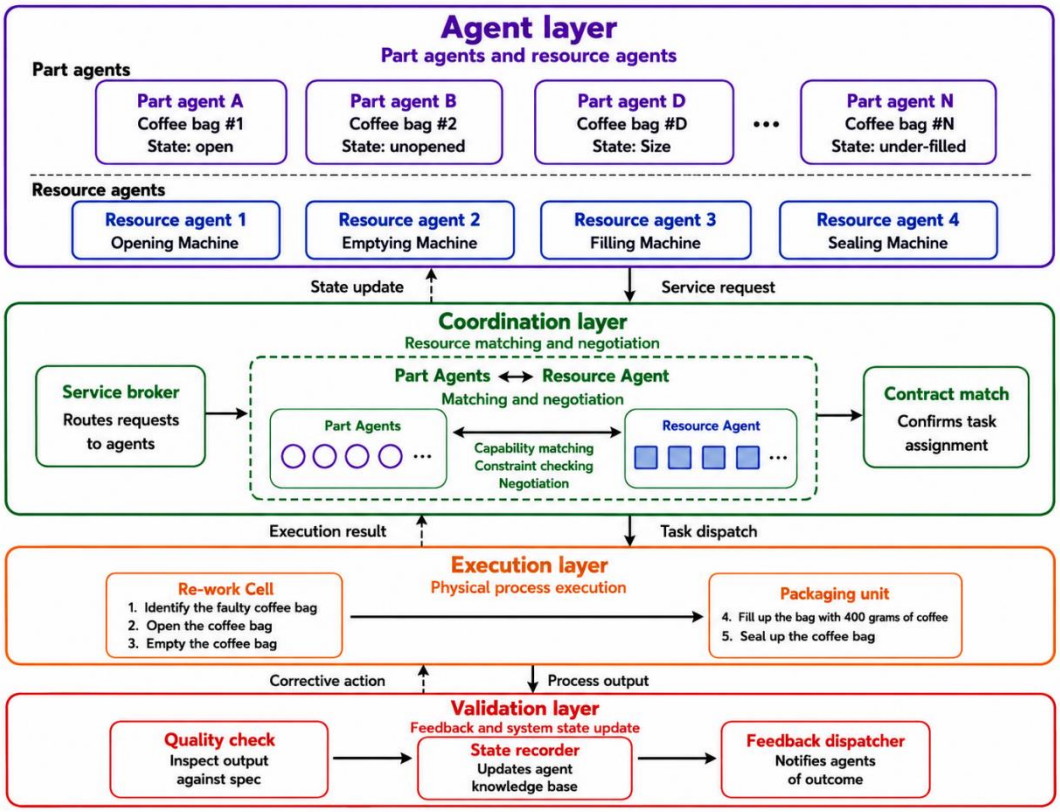


Figure 3 . Multi-agent system for automated coffee-bag rework. Part agents (bag state) and resource agents (opening, emptying, filling, sealing machines) are matched and negotiated in the coordination layer, then dispatched for execution (re-work cell → packaging unit). The validation layer inspects output, updates system state, and feeds corrective actions back through the loop.

4.2 Agent Types and Responsibilities

The foundation of the proposed system lies in the definition of two primary agent types: **part agents** and **resource agents**. Each agent operates autonomously, possesses local knowledge, and interacts with other agents to achieve system-level objectives.

Part agents represent individual workpieces, specifically coffee bags undergoing rework, and are responsible for maintaining product-related information such as processing requirements and operational goals. In contrast, resource agents represent the functional units of the system, including the opening, emptying, filling, and sealing machines. These agents encapsulate the capabilities required to perform specific processing tasks. The interaction between part agents and resource agents enables distributed task execution. The part agent requests services based on its processing goals, while resource agents provide the necessary operations depending on their capabilities and availability. This interaction structure supports flexibility and modularity within the system.

As illustrated in **Figure 4**, the architecture consists of one part agent (*CoffeeBagType1*) and multiple resource agents, including *Opening Machine*, *Emptying Machine*, *Filling Machine*, and *Sealing Machine*. Each resource agent is associated with a specific processing function, while the part agent maintains goals and interfaces that drive the rework process. The connections between the part agent and resource agents represent the communication and service relationships required for task execution. This configuration highlights the distributed nature of control and the clear separation between product logic and resource capabilities.

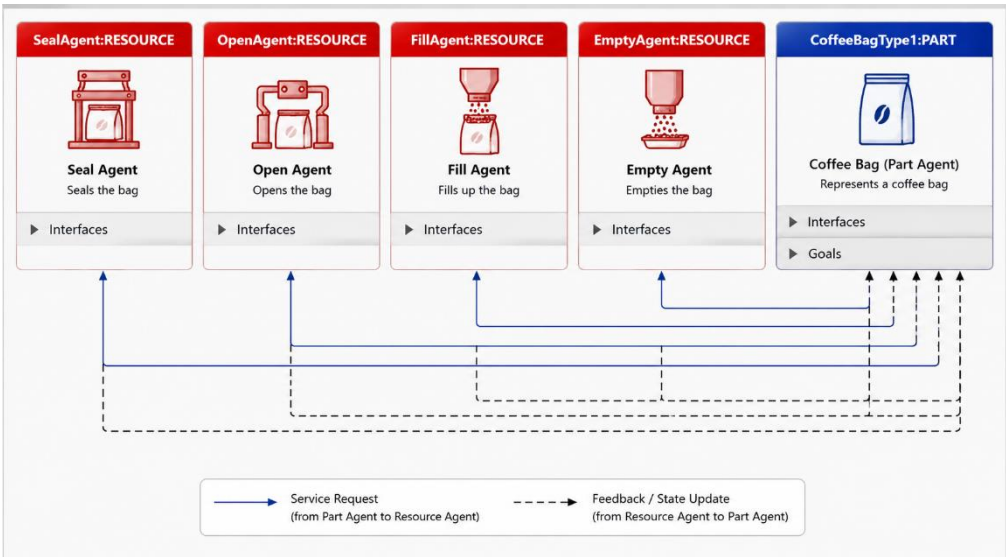


Figure 4: Conceptual representation of Part and Resource Agents in the proposed C-MAS architecture. The Coffee Bag Part Agent communicates with Resource Agents through service requests and receives feedback and state updates, enabling decentralized coordination of rework operations.

4.2.1 Part Agents

Part agents represent individual coffee bags or categories of bags within the system. Each part agent is designed as a goal-oriented entity whose primary objective is to reach a predefined final state, namely a correctly sealed coffee bag.
Each part agent maintains an internal representation of its:

- Target outcome, defining the desired end state of the bag
- Current state, indicating its progress within the rework process (e.g., unopened, opened, emptied, filled)
- Format attributes, including Size, Seal type, Material composition, Filling condition.

These attributes are critical for determining compatibility with available resources and for guiding decision-making throughout the process.
Part agents actively participate in the system by identifying required operations and issuing service requests accordingly. Rather than following a predefined sequence, each agent dynamically determines its next step based on its current state, enabling flexible and adaptive process flows.

4.2.2 Resource Agents

Resource agents represent the physical machines responsible for executing operations within the rework process. These include opening, emptying, filling, and sealing machines. Each resource agent is characterized by:

- Capabilities, which define the set of operations it can perform (e.g., sealing, filling)
- Constraints, which limit its applicability, such as: Size restrictions, Material compatibility, Capacity limitations, Machine-specific operational parameters.

Upon receiving a service request, a resource agent evaluates whether it can perform the requested operation while satisfying all relevant constraints. Based on this evaluation, the agent either accepts or rejects the request.
This autonomous decision-making process allows resource agents to adapt to varying system conditions, such as workload fluctuations or changes in product requirements.

4.3 Communication Layer

This layer plays a central role in enabling interaction between part agents and resource agents. Unlike centralized systems, where a single controller manages all decisions, the proposed architecture relies on decentralized coordination achieved through agent communication.
The interaction mechanism follows a service-oriented approach consisting of the following steps:

1. A part agent identifies the next required operation
2. The agent broadcasts a service request to available resource agents
3. Resource agents evaluate the request based on their capabilities and constraints
4. Suitable resource agents respond with acceptance
5. A task allocation decision is made based on feasibility and system conditions.

The decentralized nature of this layer enhances system flexibility and eliminates single points of failure. However, it also introduces challenges related to communication overhead and coordination efficiency, which must be carefully managed.

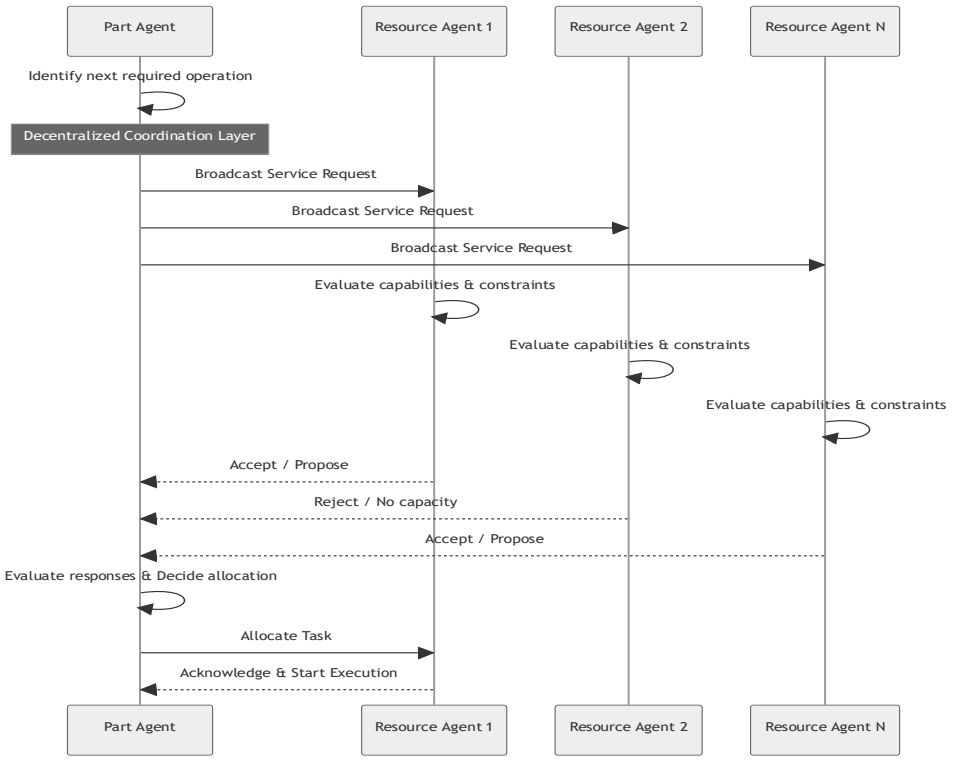


Figure 5

4.4 Execution Layer

The execution layer represents the physical realization of operations within the system. Once a task has been allocated, the corresponding resource agent performs the required operation on the coffee bag.
The rework process typically consists of the following sequence of operations:

1. Opening the coffee bag
2. Emptying its contents
3. Refilling with the correct quantity
4. Sealing the bag

The execution layer serves as the interface between the digital agent system and the physical manufacturing environment, ensuring that decisions made at the agent level are accurately implemented in practice.

4.5 Validation and Evaluation

The verification of the proposed C-MAS model is carried out to ensure that it accurately represents the logical behaviour and operational characteristics of the real-world coffee bag processing system. Validation focuses on both the structural correctness of the model and the reliability of its outputs under different operating conditions.
First, logical validation is performed by examining the process flow and confirming that all entities transition through the system in the correct sequence namely opening, filling, sealing, and, where necessary, emptying. Each agent's behaviour is reviewed to ensure that state changes (e.g., processing, blocked) occur appropriately and that no deadlocks, unintended loops, or invalid transitions exist within the system. The routing logic, particularly for defect handling, is also verified to ensure that defective items are correctly redirected without disrupting overall system flow.
Second, behavioural validation is conducted by assessing whether the interactions among agents realistically reflect manufacturing operations. This includes verifying that communication through defined interfaces results in accurate coordination between machines, and that processing constraints such as capacity limits and task durations are properly enforced. The autonomy of each agent is also evaluated to confirm that decentralized decision-making is functioning as intended within the CMAS framework.
Third, output validation is carried out by comparing simulation results with expected system performance. These outputs are checked for consistency, plausibility, and alignment with theoretical expectations or available reference data. Where applicable, multiple simulation runs are conducted to ensure stability and repeatability of results.
Finally, sensitivity analysis is performed by varying critical input parameters, such as processing times and defect probabilities, to observe their impact on system performance. This step helps to confirm that the model responds appropriately to changes and behaves in a predictable and realistic manner.

Through this multi-level validation approach, the model is demonstrated to be both logically sound and sufficiently representative of the real-world system, thereby ensuring its suitability for performance analysis and decision-making.

4.6 Architectural Characteristics

The C-MAS architecture exhibits several characteristics that distinguish it from conventional manufacturing control systems and make it particularly suitable for adaptive rework operations.

A fundamental characteristic of the architecture is its **decentralized decision-making structure**. Rather than relying on a central controller, decision-making responsibilities are distributed among autonomous agents. Part agents and resource agents independently evaluate their states, capabilities, and objectives while coordinating through runtime negotiation mechanisms. This decentralized approach reduces dependency on a single control entity and minimizes the risk of system-wide failures resulting from a single point of failure.

The architecture is also inherently **scalable**. New resources, machines, or product variants can be introduced by adding corresponding agents without requiring substantial modifications to the existing system structure. Since coordination is based on capability descriptions and runtime interactions rather than fixed process logic, system expansion can be achieved with minimal impact on already deployed components.

Another important characteristic is **flexibility**. The architecture supports dynamic adaptation to varying product conditions, process requirements, and resource availability. Through runtime goal–capability matching, part agents can request services according to their current processing needs, while resource agents can respond based on their available capabilities and operational status. This enables the system to accommodate diverse product variations and changing production scenarios without requiring predefined workflows for every possible situation.

In addition, the architecture demonstrates a high degree of **robustness**. Local disturbances, such as machine failures, temporary unavailability of resources, or workload imbalances, can be handled through agent-level adaptation and reallocation mechanisms. When a resource becomes unavailable, alternative capable resources can be identified through negotiation, allowing the process to continue with minimal disruption. This contributes to improved operational resilience and reduced downtime.

Overall, this chapter presented the design and architecture of the proposed C-MAS for the coffee bag rework process. By organizing the system into distinct architectural layers and employing autonomous part and resource agents, the proposed solution achieves decentralized control, scalability, flexibility, and robustness. These characteristics provide a strong foundation for adaptive task allocation, dynamic resource coordination, and resilient process execution in highly variable manufacturing environments.

5 Results and discussion

5.1 Experimental Execution Results

The developed C-MAS rework model was executed to evaluate the logical behaviour and coordination capabilities of the proposed decentralized architecture. During execution, the console output confirmed that the coffee bag successfully progressed through the complete rework sequence. The observed operations included:

1. Bag opening
2. Bag emptying
3. Bag filling
4. Bag sealing

The execution log produced by the system is shown in Figure below.

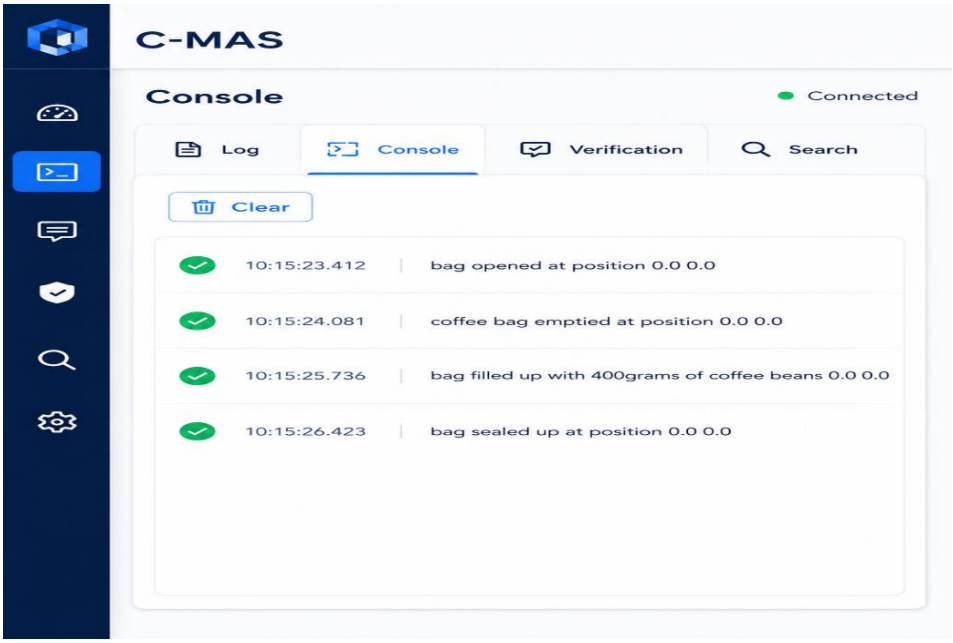


Figure 6: shows the console log generated during the simulation.

The sequential execution of these operations demonstrates that the proposed agent-based coordination mechanism correctly identified and allocated the required processing tasks. Each operation was executed in the appropriate order according to the process requirements defined for the coffee bag rework use case.

5.2 Validation of the C-MAS Coordination Logic

The obtained results verify that the implemented C-MAS architecture successfully coordinated interactions between part agents and resource agents. The part agent representing the coffee bag dynamically requested the required services based on its current process state, while the corresponding resource agents responded according to their advertised capabilities.

The execution sequence confirms that:

- The part agent correctly transitioned between operational states.
- Resource agents successfully recognized and executed compatible service requests.
- Runtime goal-capability matching functioned as intended.
- The decentralized coordination mechanism enabled process execution without centralized sequencing logic.

Unlike conventional manufacturing systems where operations are predefined through rigid control sequences, the proposed architecture allowed operations to be triggered dynamically through agent interaction. This demonstrates the flexibility of the system and its suitability for variable production environments.

5.3 Discussion of System Behaviour

The results indicate that the proposed architecture can successfully support automated coffee bag rework operations using decentralized control principles. The execution log confirms that the system achieved the desired target outcome, namely transforming a defective coffee bag into a processed and resealed product.

One important observation is the modularity of the implemented process. Each operation was treated as an independent capability provided by a specific resource agent. This separation between product goals and machine capabilities represents a key advantage of the C-MAS architecture. New processing modules or alternative machines could therefore be integrated into the system without requiring major modifications to the overall control structure.

The experiment also highlights the potential of plug-and-produce functionality. Since resource agents advertise capabilities independently, the system can theoretically accommodate resource addition, removal, or replacement dynamically. This supports the adaptability requirements associated with Industry 4.0 manufacturing systems.

Furthermore, the successful execution demonstrates the feasibility of using distributed agent communication for handling rework operations involving deformable packaging products. Traditional centralized systems often struggle with such variability due to rigid process definitions and limited adaptability. In contrast, the proposed architecture enables more flexible task coordination based on real-time system conditions.

However, the current implementation remains at a conceptual and logical validation level. The experiment primarily verifies control flow and coordination behaviour rather than physical process performance. Important industrial considerations such as communication latency, machine synchronization accuracy, real-time sensing, and physical manipulation reliability were not fully evaluated within this study.

5.4 Limitations of the Current Implementation

Although the results demonstrate successful logical execution, several limitations remain:

- The current model does not include detailed physical simulation of deformable coffee bags.
- Resource competition and simultaneous task requests were not extensively evaluated.
- Performance metrics such as throughput, cycle time, and communication overhead were not quantitatively measured.
- The implementation assumes successful execution of all operations without mechanical failure or sensing uncertainty.

These limitations provide opportunities for future work involving real-world implementation, integration with industrial communication protocols, and advanced performance optimization.

5.5 Summary of Results

Overall, the experimental results demonstrate that the proposed C-MAS architecture successfully coordinates coffee bag rework operations using decentralized agent interaction. The system correctly executed the required process sequence of opening, emptying, filling, and sealing while validating the feasibility of runtime capability-based coordination. The findings support the suitability of C-MAS and plug-and-produce principles for flexible and adaptive manufacturing systems operating under variability.

6 Conclusion and Future Work

6.1 Conclusion

This thesis set out to investigate the applicability of a C-MAS for modelling and controlling a coffee bag rework process characterized by high variability and dynamic operational requirements. Traditional centralized control approaches often struggle to efficiently manage such environments due to their reliance on predefined workflows and limited adaptability. In response to these challenges, this work proposed a decentralized, agent-based architecture capable of supporting flexible and autonomous decision-making.

The developed C-MAS framework models the system as a collection of interacting agents, where **part agents** represent individual coffee bags and **resource agents** represent processing machines. Through a service-oriented interaction mechanism, part agents dynamically request operations required to achieve their target state, while resource agents evaluate these requests based on their capabilities and operational constraints. This decentralized coordination eliminates the need for a central controller and enables the system to adapt in real time to changing conditions.

A key contribution of this work lies in the explicit modelling of product variability. By representing each coffee bag (or bag type) as an independent agent with its own attributes and state, the system can support individualized processing paths. This approach contrasts with traditional systems that rely on fixed routing logic and demonstrates a significant improvement in flexibility.

The simulation-based evaluation further highlights the effectiveness of the proposed architecture. The results indicate that the C-MAS approach:

- Reduces average processing time across different product types
- Enhance resource utilization through dynamic task allocation
- Maintains operational continuity under disturbances such as machine failures

These findings confirm that decentralized agent-based systems can provide tangible performance benefits in manufacturing environments characterized by uncertainty and variability.

At the same time, the study identifies several inherent trade-offs associated with the C-MAS approach. While decentralization increases flexibility and robustness, it also introduces additional complexity in communication and coordination. The reliance on local decision-making may lead to suboptimal global performance in certain scenarios, particularly when resource contention is high. Furthermore, increased communication between agents can impact system efficiency as the scale of the system grows.

Despite these challenges, the overall results demonstrate that the proposed C-MAS architecture provides a viable and effective solution for modelling and managing complex rework processes. The system's ability to adapt dynamically, operate without centralized control, and accommodate variability makes it highly relevant for modern manufacturing environments aligned with Industry 4.0 principles.

6.2 Answers to the Research Questions

This study adopts a conceptual engineering case study methodology consisting of use case definition, C-MAS modelling, and scenario-based evaluation. The research is design-oriented and focuses on developing a control architecture for automated coffee bag rework that addresses product variability and supports Plug-and-Produce functionality.

RQ1: How can C-MAS plug-and-produce be implemented to enable flexible reconfiguration?

This question is addressed through the conceptual design of a C-MAS-based architecture in which system components are modelled as modular agents with defined roles and capabilities. Plug-and-produce is enabled through standardised interactions and decoupled system components, allowing integration or removal of modules without extensive redesign. Flexible reconfiguration is demonstrated through scenario analysis, where alternative system configurations are constructed by modifying agent compositions. The results show that the proposed architecture supports modularity and systematic reconfiguration at the design level.

RQ2: What control strategies are required to handle variability?

This question is addressed through analysis of variability in shape and mass of granular-filled coffee bags. Based on this, relevant control strategies are identified, including adaptive handling, sensor-based feedback, and robust control principles.

These strategies are evaluated conceptually through scenarios representing different product conditions. The findings indicate that effective handling requires a combination of adaptability and robustness to accommodate uncertainty in product characteristics.

Summary, the research questions are answered through the conceptual development and scenario-based evaluation of a C-MAS-based architecture, the identification of suitable control strategies for variability, and the design of a distributed controller. Together, these contributions demonstrate a structured approach to achieving flexible and robust control in automated coffee bag rework.

6.3 Future Work

While the proposed framework establishes a strong foundation for agent-based manufacturing systems, several areas remain open for further research and development.

6.3.1 Real-World Implementation

One of the most important next steps is the validation of the proposed model in a real industrial environment. The current work relies on simulation-based evaluation, which, while useful, cannot fully capture the complexities of real-world systems.

Future research should focus on:

- Integrating the C-MAS framework with physical machines and control systems
- Implementing industrial communication protocols (e.g., OPC UA, MQTT)
- Collecting real-time data from sensors and actuators

Such implementation would provide valuable insights into practical challenges, including latency, hardware constraints, and system integration issues.

6.3.2 Integration of Key Performance Indicators (KPIs)

A critical extension of this work is the systematic integration of KPIs into the C-MAS framework. While the current evaluation uses basic performance metrics, future systems should incorporate real-time KPI monitoring and optimization as part of the decision-making process.

Relevant KPIs for the coffee bag rework system include:

- Throughput (bags processed per unit time)
- Cycle time (average processing time per bag)
- Resource utilization (machine usage efficiency)
- Work-in-progress (WIP) levels
- Queue/waiting times at each processing stage
- Task allocation success rate
- Energy consumption per processed unit
- System responsiveness (reaction time to disturbances)

Future research should focus on:

- Embedding KPI tracking within agent logic
- Enabling agents to make decisions based on KPI optimization
- Developing multi-objective optimization strategies (e.g., balancing throughput vs. energy consumption)
- Visualizing KPIs through dashboards for real-time monitoring

Integrating KPIs directly into the agent decision-making process would transform the system from reactive to performance-driven and enable continuous optimization.

6.4 Final Remarks

This thesis demonstrates that C-MAS provide a powerful and flexible approach for managing complex manufacturing environments. By leveraging decentralized decision-making and autonomous agent interactions, the system achieves improved adaptability, robustness, and scalability.

The integration of KPI-driven decision-making, advanced algorithms, and real-world implementation will be essential next steps in advancing this research toward industrial application. With these developments, C-MAS has the potential to play a key role in the evolution of intelligent and adaptive manufacturing systems within the industry 4.0 paradigm.

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