IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 18 December 2023, accepted 1 January 2024, date of publication 3 January 2024,
date of current version 11 January 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3349508

RESEARCH ARTICLE

An Altruistic-Based Framework to Support Collaborative Healing of Manufacturing Resources in a Self-Organized Shop-Floor

LUIS A. ESTRADA-JIMENEZ, SEPIDEH KALATEH, SANAZ NIKGHADAM-HOJJATI, (Member, IEEE), AND JOSÉ BARATA, (Member, IEEE)
Centre of Technology and Systems (CTS), Instituto de Desenvolvimento de Novas Tecnologias (UNINOVA), 2829-516 Lisbon, Portugal
Associated Laboratory of Intelligent Systems (LASI), FCT Campus, 2829-516 Lisbon, Portugal
NOVA School of Science and Technology, Department of Electrical Engineering, Nova University of Lisbon, 2829-516 Lisbon, Portugal

Corresponding author: Luis A. Estrada-Jimenez (lestrada@uninova.pt)

This work was supported by the DiManD Innovative Training Network (ITN) Project funded by the European Union through the Marie Skłodowska-Curie Innovative Training Networks (H2020-MSCA-ITN-2018) under Grant 814078.

ABSTRACT In manufacturing, biologicalisation defines the analysis of biological patterns as a source of inspiration to model intelligent manufacturing systems. This analysis is highly desirable as an answer to the increasing complexity of modeling current engineering solutions which are required to be self-organized, cooperative, and autonomous. Building on this line of research, our paper introduces a framework inspired by the notion of "reciprocal altruism" observed in species like vampire bats. The goal of this framework is twofold; first, to showcase the bio-inspired methodological guidelines of altruism in a manufacturing context. Second, to foster cooperative behaviors among its constitutive resources. The core idea revolves around the assignment of two roles: altruistic/donors and recipients. In this context, altruistic/donors are individuals willing to share their resources or capabilities with those in need, even at the potential cost of their own fitness. We believe that this concept has versatile applications in various manufacturing scenarios, ranging from peer-to-peer energy sharing among mobile robots to load sharing and even tool sharing. In our work, we instantiate the control logic, functionalities, and proof of concept of this altruistic approach, focusing on tool-sharing as an illustrative application. Our preliminary results demonstrate an improvement when comparing the altruistic approach with a manual one. This improvement is particularly evident when considering potential production downtime and production rate fluctuations caused by tool defects. These findings underscore the tangible benefits that bio-inspired solutions can offer in addressing the ongoing challenges of smart manufacturing, especially in terms of engineering design.

INDEX TERMS Cyber-physical production systems, smart manufacturing, self-organization, complexity theory, artificial intelligence, biologicalisation.

I. INTRODUCTION

In the last years, the global economic crisis and new market trends have made factories change their business strategies obligating companies to focus on a high level of product customization and preparing them for unexpected events and disruptions. This new way of factory control has been supported by a new vision of industry, i.e., industry 4.0 and cyber-physical production systems [1] which aim to create highly interconnected manufacturing elements that can communicate, interact, be agile, and adaptable.

Such a vision has been the result of decades of research in the context of autonomous and adaptable manufacturing systems with paradigms such as Holonic Manufacturing

The associate editor coordinating the review of this manuscript and approving it for publication was Mouquan Shen.

Systems [2], [3] and Evolvable Production Systems [4], [5]. Self-organized characteristics have been the main target of these ideas, designing systems that manage and operate themselves without external intervention.

A source of inspiration for their engineering design has been bio-inspired principles, which are fundamentally applied considering biological systems as systems composed of individual elements that can collaborate, communicate, adapt, and even heal. Such ideas are imperative as they fit perfectly well within the emergent Industry 4.0 requirements.

It is not a coincidence that the Bionic Manufacturing Systems (BMS) were explored in the 90s [6] as an early fundamental solution to provide reconfiguration in the factory shop-floor. And that some decades ahead in 2018 the term *Biologilisation* was coined by Byrne et al [7].

(Definition 1) Biologicalisation *It is the use of "bio-inspired principles in intelligent manufacturing applications to fulfill their full potential" [7], [8].*

Under the umbrella of self-organized manufacturing, several research papers have been published in the last few years. For a complete literature review of these works, please refer to [9]. Several challenges in the line of designing collective intelligence, embedded intelligent infrastructures and decentralization are still being highlighted [10].

Bio-inspired principles have been mainly applied for manufacturing control applications, e.g., the firefly algorithm, stigmergy, holonic systems, and the artificial potential field [9]. Those approaches fundamentally provide methodologies for developing autonomous manufacturing tasks, e.g., material handling, transportation, and machine configuration. An interesting approach to look for is the use of the artificial immune system as a metaphor for modeling distributed diagnosis on the factory floor. For a summary of these approaches and the context of their use please refer to Table 1.

With such background and to the best of our knowledge, we argue that self-organized collaborative healing operations at the system level in the shop floor have not been widely explored, especially considering the context of biologicalsiation in smart manufacturing. Although, bio-inspired solutions have already been discussed as a potential source of inspiration for self-haling in manufacturing [7], [8].

In this work, we consider self-organized collaborative healing as:

(Definition 2) Self-organized collaborative healing: *the capacity of a manufacturing system to cure itself based on the assumption that the constituent elements can provide "cures", or have the capacity to help others (i.e, collaborating) in a faulty situation, e.g, by sharing spare parts, sharing loads, sharing energy or sharing other related resources or capabilities.*

These ideas have been motivated by the study of the concept of reciprocal altruism, which is common in animal societies, i.e., vampire bats. Social altruistic behavior can be used as a metaphor to define roles in manufacturing resources Altruistic (or Donors) and Recipients. Those are fundamental to define such a collaborative healing environment where the main goal of having an adaptable and flexible shop floor can be realized at the cost of a minor reduction of individual fitness.

New manufacturing infrastructures with higher levels of mobility, modularity, and scalability (e.g., matrix production from Kuka [11], [12]) can be a target of these ideas. They are becoming trending considering new levels of automation [9], [13] and new decision models required for the management of autonomous mobile robots [14].

Therefore, within the current paper's context, we aim to answer the following research question (RQ), providing the identified explained hypothesis (H):

RQ: How can a manufacturing framework for healing operations be implemented while denoting self-organizing, autonomous, and collaborative collective behavior?

H: A framework with the preceding characteristics can be implemented if certain properties of the reciprocal altruism of vampire bats are studied and represented as a collective healing problem on a shop floor.

Thus, the main objective of this work is the development of a novel framework that conceptualizes and formalizes the idea of altruism on a manufacturing shop floor, providing the main conceptual, usability, and engineering principles and showcasing its usefulness in a simulated setting. This will contribute also to building in the knowledge in bio-inspired production solutions that remain as a challenge in the context of industry 4.0 [8], [15].

Considering the broad scope and application of altruistic principles, in this work, we apply it specifically in the context of manufacturing resources (known term in the literature) [4], [16].

(Definition 3) Manufacturing resource *Equipment, machine, or robot that is capable of autonomously performing a manufacturing task, i.e., transportation, pick and place or drilling.*

We expect the current framework can be applied specifically in emergencies, considering also that a high percentage (89% according to [17], [18]) of equipment failure occurs due to random reasons.

(Definition 4) Emergency machine (resource) failure *Unexpected failure of manufacturing resource that was not predicted and/or occurred randomly and needs to be solved within a minimum production downtime.*

The rest of this paper is organized as follows.

Section II examines in detail the concept of Altruism in Vampire Bats and proposes a Biolicalisation approach to it. Section III provides an insight of the vision and some practical implications of this concept. Section IV proposes a framework where these ideas are instantiated and formalized with an activity diagram, a class diagram, and a generalization

TABLE 1. Collection of bio-inspired approaches in the context of manufacturing self-organization.

Ref	Mechanisms	Context (example)
[19]	Firefly Algorithm	Self-organized control of manufacturing resources by means of attraction.
[20]–[22],	Artificial Immune System	Distributed diagnosis by abstraction manufacturing agents as b-cells, cure agent and diagnosis agent.
[23]–[31]	Stigmergy	Using the concept of pheromones to communicate manufacturing agents indirectly.
[23], [29], [32]–[38]	Holonic systems	Manufacturing control is done by the abstraction of elements as holons: self-regulating entities that can communicate and act autonomously.
[39], [40]	Chemical abstract machine	The reaction of molecules is used as an analogy to represent the composition of manufacturing modules.
[41]–[44]	Artificial Potential Fields	Concept of field attraction to transport products to resources.

of altruistic strategies. Section V proposes an experimental setup to test these ideas, various assumptions are described as well as an analysis and discussion of the results are presented. Section VI presents some limitations and future works. Finally, Section VII presents final remarks and conclusions.

II. ALTRUISM IN VAMPIRE BATS - A BIOLOGICALISATION CONCEPT

The methodology to develop the self-organized manufacturing solution follows the approach presented in [9]. Their main steps are summarized below.

A. ALTRUISM AND RECIPROCAL ALTRUISM

In a seminal article within the field of altruism research, Trivers [45] introduced the concept of reciprocal altruism hypothesis, which has since become a cornerstone of understanding altruistic behavior. Trivers coined the term ‘‘altruism’’ to refer to actions aimed at benefiting someone other than the individual performing the altruistic act. He employed principles from evolutionary biology to elucidate the underlying dynamics, particularly focusing on the interplay of costs and gains [46].

In circumstances involving life-threatening risks like starvation, where it is uncertain which individual will succeed in procuring sustenance on any given occasion, Trivers [45] contended that reciprocal altruism can establish itself as an evolutionarily sustainable strategy. However, this can occur only when those who successfully obtain food receive an excess beyond their immediate requirements and are willing to share it with their neighbors.

Trivers’ key insight was that acts of kindness and charity often lead to reciprocal favors in the future, ultimately resulting in a net gain for the initial giver. This perspective suggests that engaging in benevolent actions within strategic social networks can foster a cycle of reciprocal favors. This, in turn, has the potential to enhance individual well-being and, on a broader scale, contribute to the improvement of the entire community or society [46], [47].

Trivers’ reciprocal altruism hypothesis emphasizes that altruistic behavior is not solely motivated by selflessness. Instead, it can be based on a strategic calculus. Individuals recognize the benefits of helping others and receiving help in return. This creates a mutually advantageous dynamic within social networks [48]. This concept offers valuable insights into the evolution of cooperative behavior and the dynamics of human social interactions [49], [50].

A remarkable illustration of altruism can be witnessed in the behavior of vampire bats. These bats primarily sustain themselves by feeding on the blood of cattle, often enduring periods of food scarcity, with a potential survival limit of up to three nights without nourishment [51]. Ordinary vampire bats, known to die after 70 hours of fasting, frequently exhibit a remarkable act of altruism where hungry bats receive sustenance through regurgitated blood from their fellow roostmates [52], [53]. This natural, energy-intensive sharing of food occurs among both kin and non-kin bats and can even be artificially induced. The phenomenon of food-sharing among vampire bats provides an intriguing model. It can be used to investigate the mechanisms behind cooperative behavior and social bonds. This model is applicable not only in the animal kingdom but also has implications for understanding cooperation and interdependence. These implications extend to human societies and industrial contexts [54]. In such settings, collaboration, individual autonomy, and survival in times of resource scarcity are critical factors [55], [56].

B. RELATION BETWEEN ALTRUISM AND AUTONOMOUS MANUFACTURING SYSTEMS

A self-organized manufacturing shop-floor is a system capable of independently carrying out its core functions like handling, maintenance, and control without the need for external human intervention. These manufacturing requirements are addressed by autonomous production systems with self-management capabilities [9], [57]. Furthermore, an intelligent architecture facilitates the utilization and sharing of modular, task-specific components, reducing the manual engineering effort needed for system configuration and reconfiguration [58].

Achieving sustainable, self-organized, and collaborative manufacturing relies significantly on effective communication and cooperation among autonomous vehicles, particularly during critical moments when assistance is required, such as energy depletion, tool repairs, or load sharing. This is where the concept of altruism introduces innovative solutions [59]. Reciprocal altruism's internal cooperative behavior ensures that unrelated agents come to each other's aid when needed, facilitating self-management and ongoing collaboration within manufacturing resources [60]. This occurs when agents have established strong and dependable connections, enabling them to make autonomous decisions that benefit the collective effort. Table 2 encompasses the altruistic concept mapping within different manufacturing scenarios pointing out the associated target, the health-related issue, the possible associated indicator and the altruistic strategy to be used.

C. SUPPORT OF TECHNOLOGICAL ENABLERS

The development of new technological enablers and computational tools is underway to achieve autonomy, reconfigurability, and flexibility in manufacturing processes. Many of these emerging technologies have the potential to support cooperative and altruistic behaviors. Intelligent cooperative agents, for instance, can facilitate resource awareness and enable distributed communication. Reusable and shareable intelligent manufacturing modules offer the capability to reallocate resources when needed. These modules can be reused and shared, providing flexibility in resource allocation. Meanwhile, smart perception systems and artificial intelligence methods come into play. These systems enable the monitoring of physical variables, offering insights into the status of individual resources. In summary, the combination of reusable modules and advanced perception systems facilitates efficient resource management in intelligent manufacturing. Hardware such as wireless energy chargers can facilitate the sharing of energy consumption among various resources. Consequently, it is evident that the integration of altruistic behavior is feasible within the current technological landscape, fostering enhanced cooperation and adaptability in manufacturing processes.

Cloud computing [61] allows manufacturers to store and process vast amounts of data and access computing resources on-demand through the internet. In self-organizing manufacturing systems, seamless data sharing and real-time collaboration are facilitated. Cloud-based solutions offer scalability and flexibility, enabling manufacturing systems to efficiently adapt to changing demands and conditions. This adaptability is crucial for self-organization, as it enables manufacturing systems to reconfigure and optimize themselves based on real-time data and feedback [62].

In self-organized manufacturing, intelligent agents play a crucial role in coordinating and optimizing various aspects of the production process. These agents can analyze data from sensors, machines, and other sources to make informed decisions about resource allocation, production scheduling, and quality control. They can also communicate and collaborate with other intelligent agents and platforms, facilitating the exchange of information and decision-making within the manufacturing system [63].

III. VISION AND IMPLICATIONS

This section offers key insights into the vision and broad implications of the altruistic framework.

A. VISION

The proposed framework relies on the definition of intelligent resources that have the capacity for communication, reaction, and decision-making. These resources are elements on the shop floor that can perform a manufacturing operation, e.g., transport, machining, pick and place, welding, etc. Based on the concept of altruism we define Recipient and Altruistic resources.

- **(Definition 5) Recipient Resources**: *Resources that in their current conditions have detected or foreseen a type of anomaly in their operation and have required some assistance or repairing action from another resource to continue with their current task.*
- **(Definition 6) Donor or Altruistic Resources**: *Resources that in their current conditions have received the request of healing or repairing from a Recipient one. They can assist, repair, or provide a cure by sacrificing part of their fitness and simultaneously completing their own task(s).*

As it is shown, the relation of both roles is bidirectional. While a Resource becomes the Recipient and the other Altruistic, the first one asks for healing and the second one heals. This relation can be seen in Fig. 2.

Taking advantage of current digitized technologies and available IT infrastructures, our approach's vision uses the altruist orchestrator concept to make communication available between the resources.

(Definition 7) Altruist Orchestrator is defined *a software platform that coordinates altruistic requests and provides altruistic responses according to the needs and availability of the resources in the shop floor*. This coordination makes feasible physical collaboration (altruism). This description can be visualized in Fig. 3.

B. SCENARIOS AND PRIORITY

In a manufacturing shop floor, different altruistic scenarios can be envisioned by considering the number of individuals in need and the available candidates to offer help. In this subsection, we classify them considering this criterion and provide insights into the priority applied. A summary of this classification is shown in Fig. 4.

1) SINGLE DONOR - SINGLE RECIPIENT

There is one resource that requires assistance (Recipient) and just one candidate (Donor) that can provide it. There are not priorities in this scenario.

2) MULTIPLE DONORS - SINGLE RECIPIENT

There is one resource that requires assistance (Recipient) and several candidates (Donors) that can provide help. The chosen Donor will be the one that offers the best (optimal

TABLE 2. Collection of analogies between altruism and cooperative self-healing in manufacturing.

Context (Hungry vampire bat)	Resource Target associated (Bat)	Health related issues (Not enough food / blood)	Indicators associated (Donors own blood capacity)	Altruisitic strategy (Flying towards the target and regurgitate a portion of food)
Peer-to-peer energy sharing	AGV	Not enough energy	Lead time, Current energy, Distance towards the target	Move towards target AGV and share energy
Tool defect in a robot	Robot: tool	Tool wear	Tool wear, Cycle time, Tool compatibility	Exchange the tool
Overload of mobile robots	AGV	Robots payload	Cycle time, Current energy, Donor own payload	Cooperative transportation of load

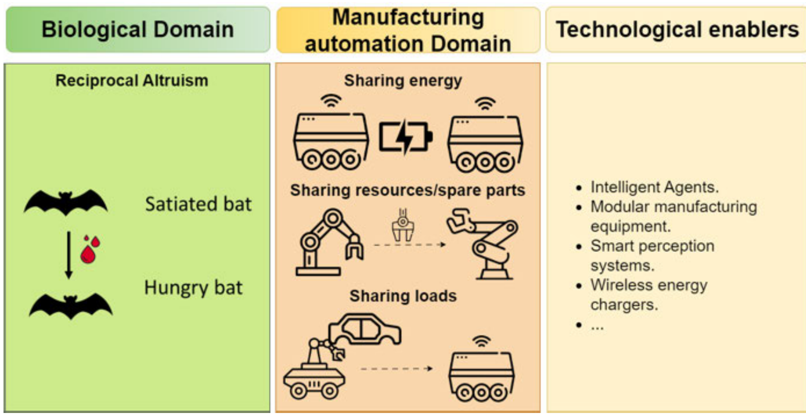


FIGURE 1. Biologicalisation approach.

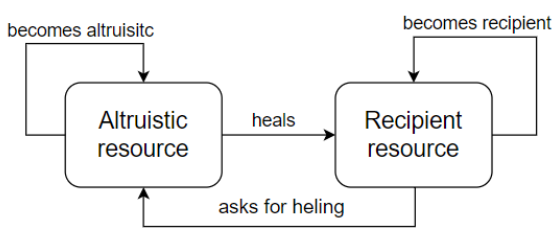


FIGURE 2. Vision of an altruistic smart manufacturing environment.

characteristics). These characteristics can depend on the type of altruistic application:

- For energy sharing: due time, remaining energy, the distance toward the recipient, etc.
- For tool sharing: due time, remaining life of the tool distance towards the recipient, payload, etc.

A multi-criteria decision-making approach (MCDM) can be useful to find such candidates.

3) SINGLE DONOR - MULTIPLE RECIPIENTS

In this case, multiple resources require assistance (Recipients) and there is just one Donor available. The recipient to be chosen will be the most urgent one. The most urgent Recipient will be chosen based on specific application characteristics. The level of urgency will depend on:

- For energy sharing: due time, delay cost, the distance towards the recipient, etc.
- For tool sharing: due time, delay cost, etc.

MCDM can be also a useful approach to quantify and categorize the level of urgency.

4) MULTIPLE DONORS - MULTIPLE RECIPIENTS

This scenario is a combination of the two previous ones, i.e., several Donors and several Recipients. The strategy consists on:

1) Finding the most urgent resource.
2) Choosing the optimal donor candidate for the resource.
3) Applying the altruistic strategy.
4) Continuing the cycle with the next more urgent recipient.

C. EFFECT OF BACKLOG

The application of altruism comes with a predetermined delay (backlog), especially from the side of the chosen Donor. The Donor should stop its primary task to start the sharing process and help the resource in need. Under these circumstances, it should be stated that the cost of the delay is assumed to be negligible compared to the delay cost of the Recipient's task.

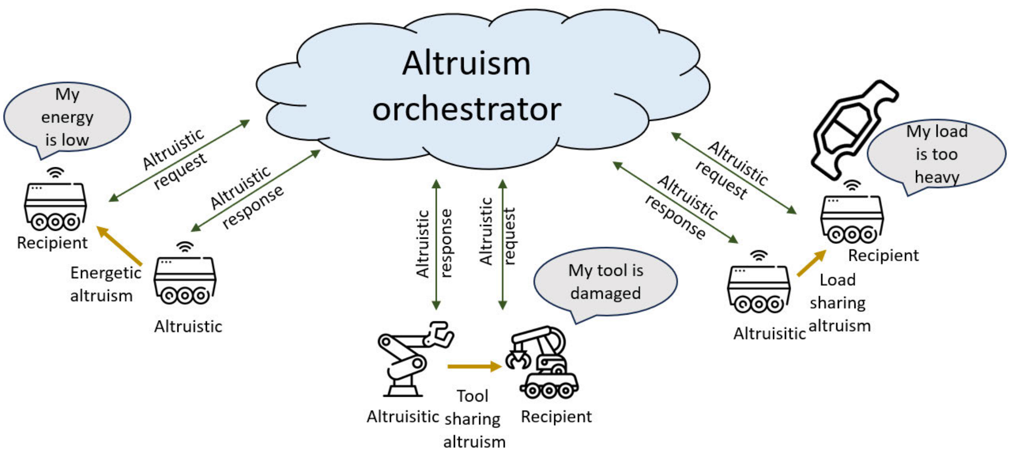


FIGURE 3. Collaborative altruistic behavior based on the concept of orchestrator.

Otherwise, the application of an altruistic process should be reconsidered. To quantify, the Donors' associated backlog, in this work three time variables have been identified as presented in ec. (1)

$$T_b = T_1 + T_2 + T_3 \tag{1}$$

where:

T_{b} : Backlog time
T_1 : Encounter time
T_2 : Sharing time
T_3 : Return time

Figs. 5a and 5b showcase the specified backlog for an energy-sharing and for a tool-sharing scenario. In the second case, we assume that an ''auxiliary'' mobile robot is in charge of the logistics of the tool-sharing process as the cells are static.

D. STRATEGIES FOR RECOVERY

Chosen Donors not only have the capacity to help others but also should be able to continue with their current operations after the altruistic process finishes. This is a crucial requirement to become a Donor. Therefore, there should be no issues with post-normal working conditions. For instance, if a mobile robot needs to supply energy to another in need, it will be required (1) to have enough energy to share and (2) enough energy to continue its current task(s).

After completing the altruistic process, some considerations that could be made to further support the process include:

- Possibility of manual intervention to maintain/replace tool/resource of the element used as Donor. For example, in the case of the energy sharing application and after the emergency has been resolved, it could be advisable to have a manual replacement of the battery of the robot.
- Having some redundancy in the resources to be shared. For instance, in the energy-sharing application, extra batteries could be stored in the robot itself or in a specific place that could work as a replacement. This is analogous to the biological process where bats can share food (or energy in the case of mobile robots) until they can find a different source (in this case the other source could be the manual replacement or the place to store extra batteries).

E. TARGET ORGANIZATIONAL PRODUCTION

New levels of automation comprise shop floors with higher levels of mobility, flexibility, and adaptability [9]. These characteristics are different from traditional manufacturing scenarios. Thus, one of the target production organizations of this work is the Matrix Production proposed by KUKA [12]. The idea is to separate shop-floor logistics from production, removing fixed material flows and rigid connections between stations. In this approach, the shop floor is composed of a grid of stations that are not tailored to specific products. A tool store supplies the needed equipment to customize the cells. While a warehouse provides production parts. An Automated Guided Vehicle (AGV) store offers transportation (AGVs) to move tools and materials to each station. This system allows for self-transformation, scalability, and control over capacity usage and bottlenecks [9]. Given its flexibility and mobility, we see this concept as an ideal scenario to demonstrate an altruistic and sharing process. Fig. 6 shows a sketch of the Matrix Production.

IV. SEQUENTIAL LOGIC, METHOD AND ALTRUISTIC FRAMEWORK

The current section introduces a formal representation of the framework, class diagrams, sequential logic, and suggested methods for multi-criteria decision-making.

A. CLASS DIAGRAM

Distinct classes embody manufacturing resources, each defining unique attributes and functionalities. These classes

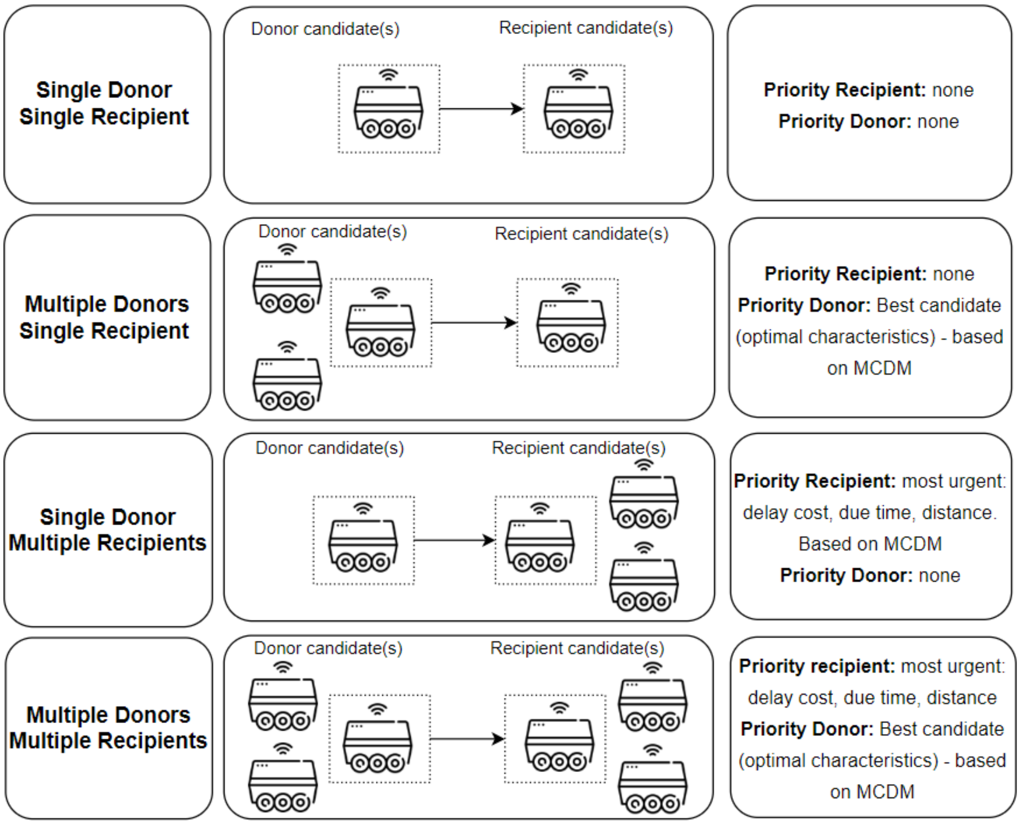


FIGURE 4. Scenarios of altruism and priority.

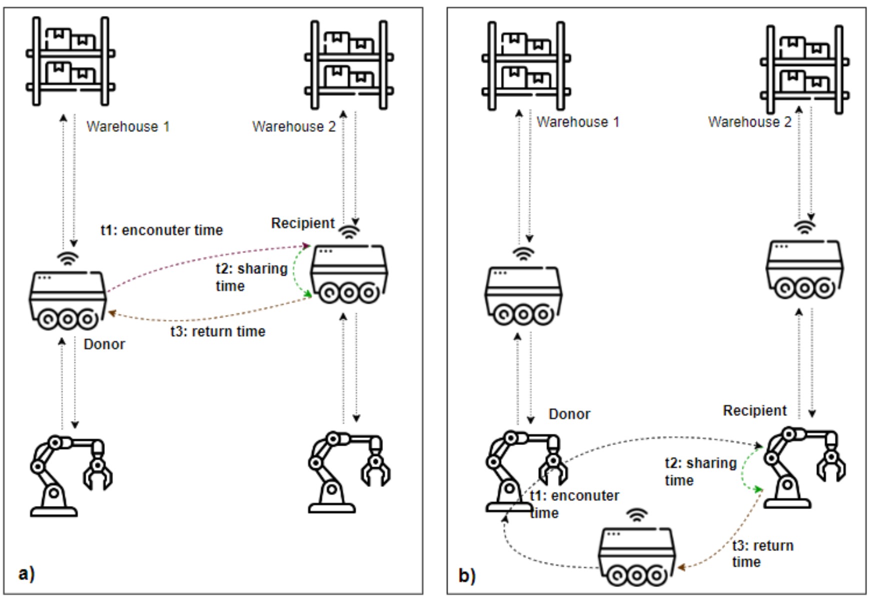


FIGURE 5. Effect of backlog in an a) Energy sharing and in a b) Tool sharing altruistic scenario.

stand as fundamental components within the framework (see Fig. 7).

- **Resource**: Abstract class that defines common attributes and methods of manufacturing resources. The main components are ID (Unique identifier per resource), Role (Altruist or Donor), Status (Idle, or in operation), Position (location with respect to a coordinate axis), ProducDrivenCycleTime (Expected time that the resource will be in operation), ListOfTasks (List of activities that the resource will be part of).

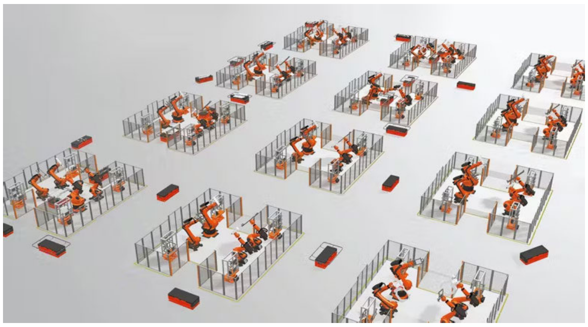


FIGURE 6. Kuka Matrix Production. Image from KUKA [12].

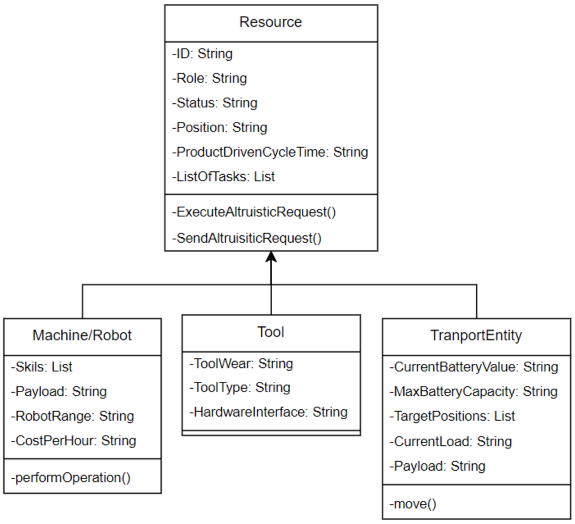


FIGURE 7. Class diagram of the resources of interest.

- **Machine/Robot**: Child class of Resource. Specifies machines or robots with concrete capabilities or skills, some attributes of consideration are the maximum payload, the max range (in the case of a robot), and the cost per hour.
- **Tool**: Child class of Resource. It specifies end effectors or tools that can be used and interchanged by various robots. Some attributes of consideration are the ToolType, the HardwareInterface it has, the ToolWear which specifies its health status and the possible need to be replaced.
- **Transport Entity**: Represents mobile robots for the transport of goods and consumables. Attributes of consideration for the current framework are the current energy available, the maximum capacity of battery storage, the targeted positions, and the payload.

B. GENERAL ACTIVITY DIAGRAM

Various stages have to be considered during the execution of the framework. When a resource detects it has an anomaly, its primary task will stop (it will be assigned the role of "Recipient"). Immediately, it will publish an altruistic request in a broker infrastructure.

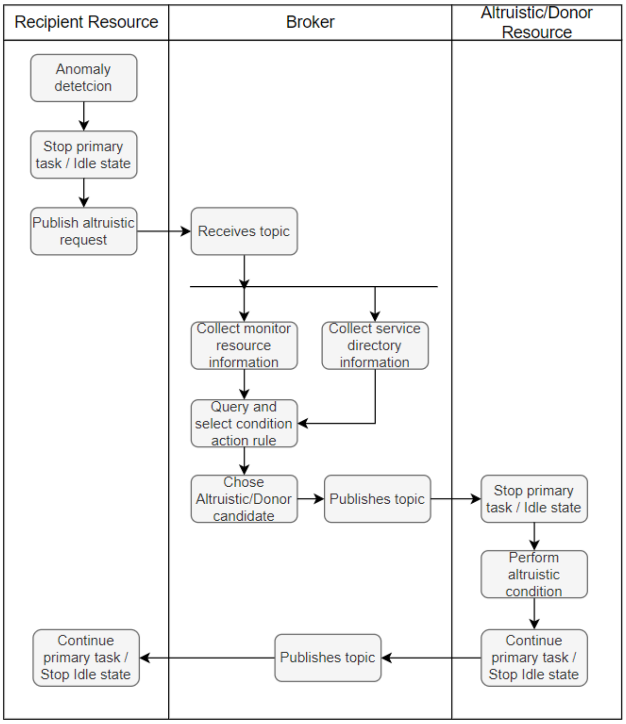


FIGURE 8. General activity diagram of the altruistic behaviour.

When launching this event, the monitoring information of all resources will be extracted from a Service Directory (later it will be described as a Yellow Pages component). Depending on the context of the situation, e.g., the position of resources, type of failure, specific parameters, etc., a specific candidate will be chosen and a specific execution activity will be launched. The candidate will be chosen based on: the identification of Recipient attributes, filtering possible Donor candidates (which fulfill the specific requirements), and an optimal Donor selection.

The chosen Altruistic candidate will stop its primary task until the altruistic condition has been executed (after the sharing process has been completed, i.e., tool sharing or energy sharing). After that, both the Recipient and Altruistic resources will return to normal conditions. To see this sequential flow please refer to Fig. 8.

C. GENERALIZATION OF THE CONDITION ACTION ALTRUISTIC STRATEGIES: TOOL SHARING PROCESS

To generalize the altruistic strategies, we focus this paper on the instantiation of tool-sharing in the case of faulty tools.

The strategy starts with the identification of the tool in a faulty state. Then, the candidates' filtering stage checks the candidates from the pool of available resources that can fulfill the minimum criteria to serve as a Donor. Some examples of such conditions are the tool payload, tool wear, etc. Candidates are assessed using criteria (C) such as payload, distance, and cycle time to select the best fit. Refer to Fig. 9 for the process logic.

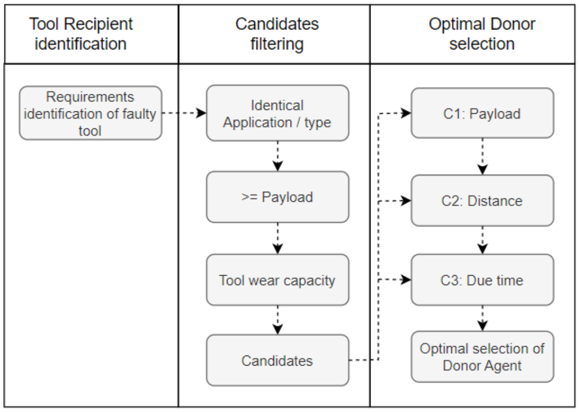


FIGURE 9. Tool sharing selection; C represents the selection criteria.

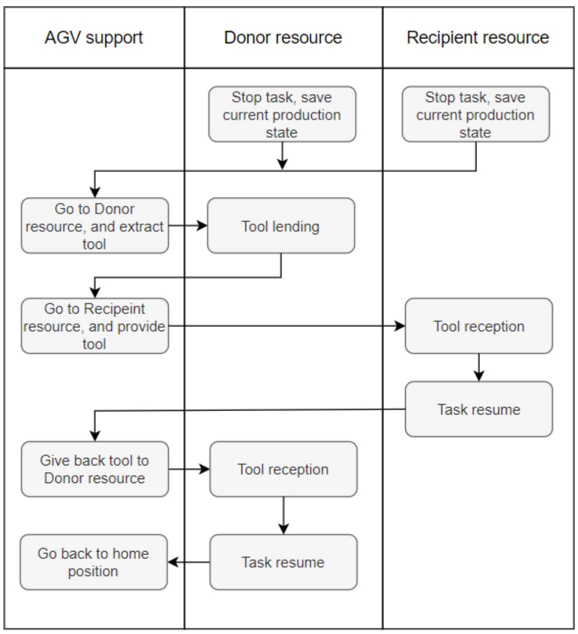


FIGURE 10. AGV support as an enabler of the altruistic behavior in the tool sharing process.

In terms of resources, we make use of "AGV support". It is an element that can be used as a transportation means from the Donor resource to the Recipient resource and vice-versa. Such an assumption is needed to overcome the limitation of having fixed robots/machines that cannot move and therefore cannot easily share their resources. From this perspective, the AGV support will extract and lend the tool to the Recipient and Donor respectively. This process can be seen in Fig. 10.

D. MCDM FOR CHOOSING THE BEST DONOR CANDIDATE AND MOST URGENT RECIPIENT

Multi-Criteria Decision Making (MCDM) is a method that considers different qualitative and quantitative criteria to be fixed to find the best solution [64]. MCDM is used in the context of the current research to find the optimal Donor candidate or most urgent Recipient based on specific parameters it contains. In this work, we primarily focus on parameters to find the optimal Donor candidate. Considering a general formulation of MCDM [64], the different alternatives available are defined as shown in eq. (2).

TABLE 3. MCDM matrix considering the various candidates (A), the criteria used to evaluate them (C), and their weights.

MCDM Matrix	C_1	C_2	...	C_n
A_1	x_{11}	x_{12}	...	x_{1n}
A_2	x_{21}	x_{22}	...	x_{2n}
...	...	...	x_{ij}	...
A_m	x_{m1}	x_{m2}	...	x_{mn}

$$A = A_i \mid i = 1, 2, \ldots, m \tag{2}$$

where A represents the various available Donors (e.g., Tool 1, Tool 2, Tool 3) and m its existing number. The criteria used to evaluate each Donor candidate can be seen in eq. (3).

$$C = \{C_j \mid j = 1, 2, \ldots, n\} \tag{3}$$

C represents the criteria used to evaluate each possible candidate (e.g., tool wear, payload) and n its number. Eq. (4) represents a set of normalized weights W that can be used to evaluate the importance of each criterion. In the current context, this can be defined by experts who defined the importance of each criterion in the altruistic process.

$$W = \{w_j \mid j = 1, 2, \ldots, n\} \tag{4}$$

As outlined in Taherdoost [64], the information for MCDM can be structured in a matrix format, as exemplified in Table 3. This matrix notation will guide us in identifying the optimal Altruistic candidate.

The main objective of MCDM is to score alternatives and the order from best to worst. There are various methods with different characteristics to be used [64]. In this research, we use the TOPSIS method. It involves normalizing a matrix, calculating Euclidean distances between alternatives, and ranking them based on their TOPSIS score. Details on the implementation can be found on [65]. The next section of the paper explains the implementation of TOPSIS using a built-in Python library.

E. FRAMEWORK DESCRIPTION

The sequential logic and methodological landscape presented in this section are used as a basis to formalize and instantiate the framework shown in Fig. 11.

The description of the framework is presented below:

- **Broker**: It is the software bridge that integrates and acts as an intermediary between the components of the altruistic framework, i.e., yellow page resources and condition action altruistic strategies. It facilitates the data management of the physical devices by sending and receiving altruistic requests. See Fig. 8.
- **Event-driven monitoring**: A component that is based on local physical information. It can monitor a possible anomaly and thus send a requirement of altruistic help

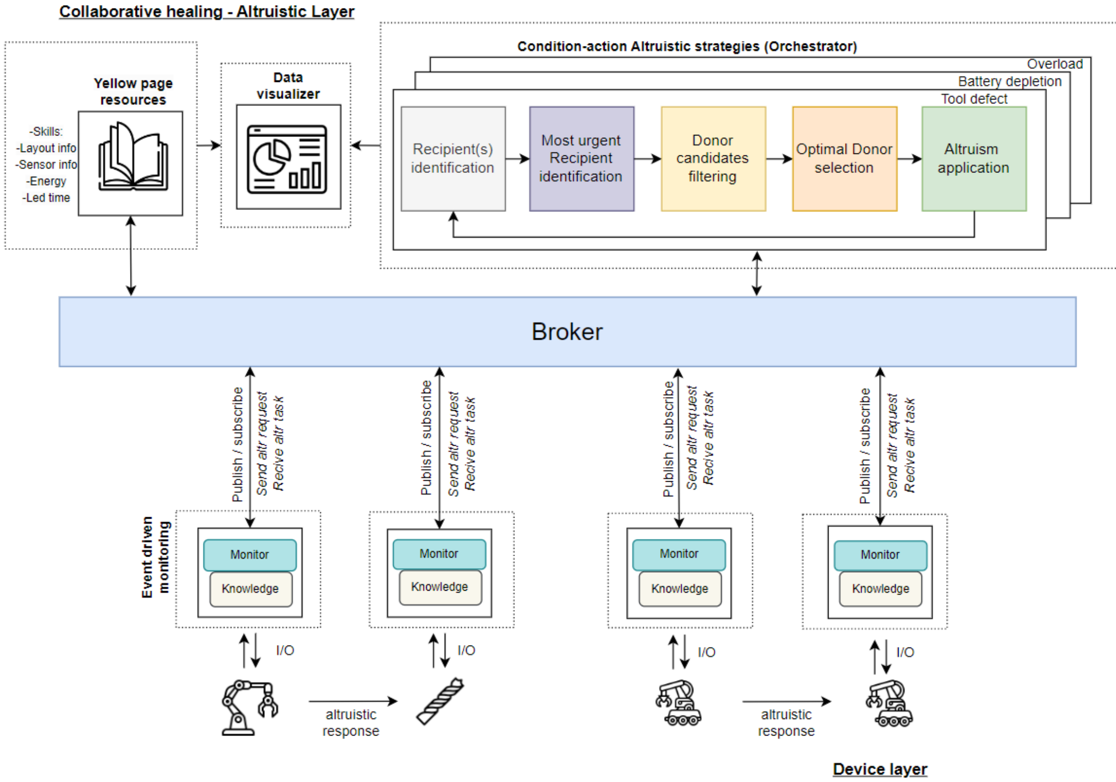


FIGURE 11. Altruisitic-based framework for collaborative healing operations.

to the system network. It is based on internal knowledge representation of the resource.

- **Yellow page resources**: It provides data representation and information about available manufacturing resources as well as their main attributes. These characteristics are used to identify Altruistic candidates and are input for the condition action altruistic strategies.
- **Condition action altruistic strategies**: A set of rules that define and orchestrate the behavior of altruistic and recipient resources after a recipient in need has been identified. Such rules define also the optimal altruistic candidate based on multi-criteria decision-making and filtering rules. See Figs. 8, 9, 10.
- **Data visualizer**: Interface that allows visualization of information of resources and their attributes.

The next section provides the validation and a first implementation of the framework presented.

V. VALIDATION

This section describes the simulated proof of concept used to verify the effectiveness of the proposed framework. We start by describing the use case, describing the steps for the Altruistic behavior implementation, and analyzing the results obtained.

A. SIMULATED USE CASE DESCRIPTION

The methodology proposed can be used to determine Altruistic resources that have the capability of helping other resources in need (faulty conditions) and execute the altruistic operation to maintain a reduced production downtime. This is important considering the current highly reconfigurable manufacturing solutions like the KUKA matrix production composed of a matrix of production cells, and where material handling is fully automated with mobile robots. Inspired by this concept, the example below illustrates a simulated scenario of a shop floor composed of:

- Warehouse storage place: Place to store raw materials and starting and finishing point for the material handling.
- Robots: Resources capable of performing a specific operation/task/process.
- AGVs: Resources in charge of the material handling of the product from the warehouse to each one of the robots.
- AGV for altruistic support: Mobile robot used for transportation of the end effector or tool that is going to be shared between two robots.

The simulation has been implemented using the software NetLogo (see Fig. 12), commonly used to study complex behaviors in multi-agent systems. The provision of sliders allows the modification in real time of specific parameters used to simulate the failure of an end effector. Also, it provides parameters for the MCDM to choose the optimal donor candidate. The parameters considered are:

- Robot location and location of the altruistic support.
- Percentage of tool wear of the end effector of the robot.

- End effector/tool wear threshold.
- Payload.
- Due time of the operation of each product.

B. IMPLEMENTATION

Fig. 13 presents the tools used the evaluate the usability of the framework. As stated, the software used to simulate the various elements on the shop floor including the altruistic support AGV was Netlogo. Text files (.txt) were used as a media of information exchange between NetLogo and the Broker to facilitate the information integration. The Broker has been developed using the paho-mqtt library, which implements the machine-to-machine protocol. It facilitates the publishing and subscription of various functionalities within the framework. Additionally, the yellow page resources and condition-action altruistic strategies have been implemented through Python scripts. The MCDM has been implemented using the pymcdm 1.2.0 library [66].

Finally, the data visualizer was implemented using the toolkit tkinter, which is a standard interface for the development of graphical user interfaces.

C. ALTRUISTIC DECISION-MAKING FOR TOOL SHARING - SIMULATED SCENARIO

The decision-making implementation represents the process of choosing the optimal Donor candidate in the case of a faulty situation. In our scenario, after the simulation of the failure of a tool (in Robot 1), with process parameters specified in Table 4, the requirement of finding a possible donor is launched. In this example, the tool failure is considered when the ‘‘current tool condition’’ is less than or equal to the ‘‘allowed tool condition’’. Here the current ‘‘tool condition’’ is 50% and the ‘‘allowed tool condition’’ is 80%. Thus, a failure is reported. The requirements are based on the specified characteristics of the application, payload, and allowed tool condition as depicted in Table 5. These parameters have been chosen for simulation purposes.

In the simulation, the candidates with such characteristics are filtered. Those are presented in Table 6. After that and as explained in the section IV-D, the optimal donor candidate is calculated based on TOPSIS. For simulation purposes, we considered the normalized weights of each candidate as equal to 0.25 (considering that there are 4 evaluation criteria).

Table 7 shows the scores obtained using this strategy. It can be concluded that the candidate that has the best conditions to serve as a donor is Robot’s 4 tool. Thus, altruism will be applied using this resource.

As it was depicted in Fig. 9 and Fig. 10, the basic strategy consists on:

1) To stop the movement and operation of Robot 1 (R1) and Robot 4 (R4), as well as their associated AGVs.
2) To initiate the movement of altruistic support towards R4 and take momentarily its tool.
3) To redirect the tool towards R1 (failure) and continue with its task.
4) After R1’s task has been finished, redirect back the AGV support with the shared tool to its previous owner (R4).
5) To continue with the normal operation of R4 and direct back the altruist support to its home position.

After this, the altruistic process is finalized. The logic of the altruistic process as well as the preliminary results of the data visualizer can be seen in Fig. 14.

D. DOWNTIME COMPARISON BETWEEN ALTRUISTIC (AUTOMATIC) AND NON-ALTRUISTIC OPERATIONS (MANUAL)

This section aims to extend the findings from the prior scenario, delving into the advantages and constraints of the concept in relation to downtime by contrasting the altruistic (automatic) approach with the non-altruistic approach (manual operation).

Several assumptions and preconditions are made as there could be many variabilities/scenarios in which altruism could be applied. Those are specified below.

- Considering the scenario from Fig. 12, the production consists of a single operation process, with tools and robots that have identical functionality.
- Each task consists of transporting the raw material from the warehouse toward the robot in front, executing a specific operation during a defined amount of time (processing time), and going back to the warehouse to store the material.
- If there are no failures in the process, all operations start and finish simultaneously, as the processing time is identical.
- After a failure occurs and there is a need for tool sharing, we assume that the affected robot returns to a healthy state momentarily.

We establish specific conditions for this simulation, which apply to altruistic and non-altruistic approaches. These conditions include:

- The manual tool exchange process consists of a human operator going to the robot and manually subtracting and changing the tool. The variables considered here are *time for manual tool exchange*, which is the time required for the operator to take and extract the tool and replace it, and the *operator preparation and reaction time*, which is the time the operator needs to get ready and to start the tool exchange. In this simulation, the sum of these values is considered the *total downtime for the manual process (non-altruistic)*.
- In the altruistic process we specify two essential sources for downtime. The first one is the *downtime from the side of the Recipient robot*, which is the time the Recipient robot has to wait for the transportation of the tool from the Altruist side once the altruistic request has been launched. The second one is the *downtime from the side of the Altruistic robot*, which is the time the Altruistic robot has to wait for transportation of the shared tool

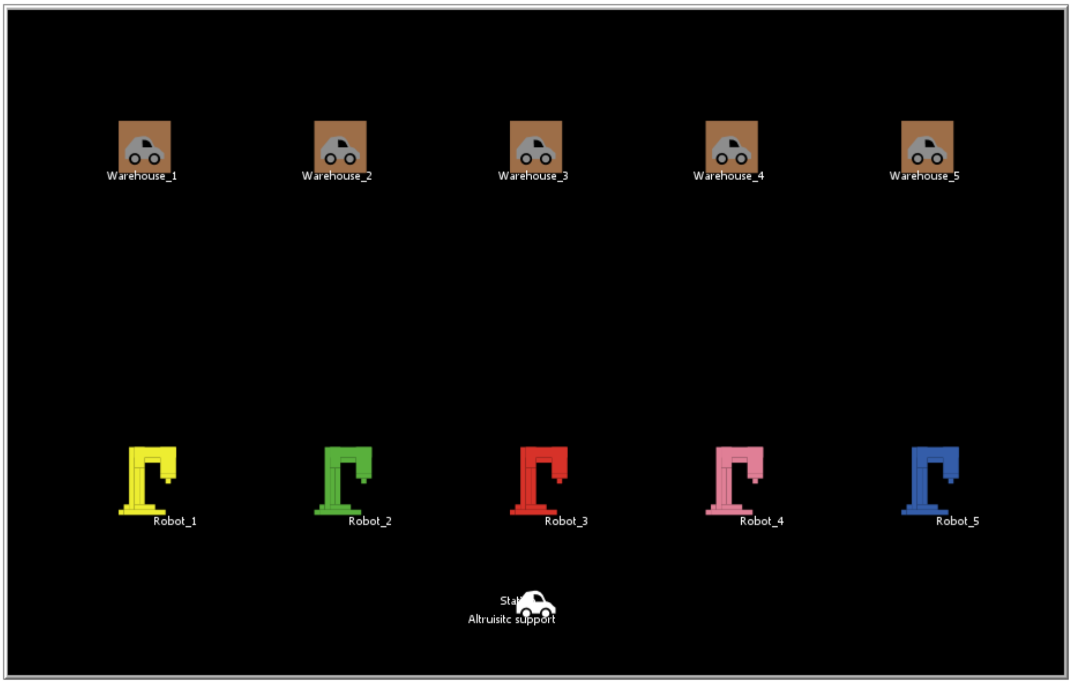


FIGURE 12. Simulated shop-floor in NetLogo.

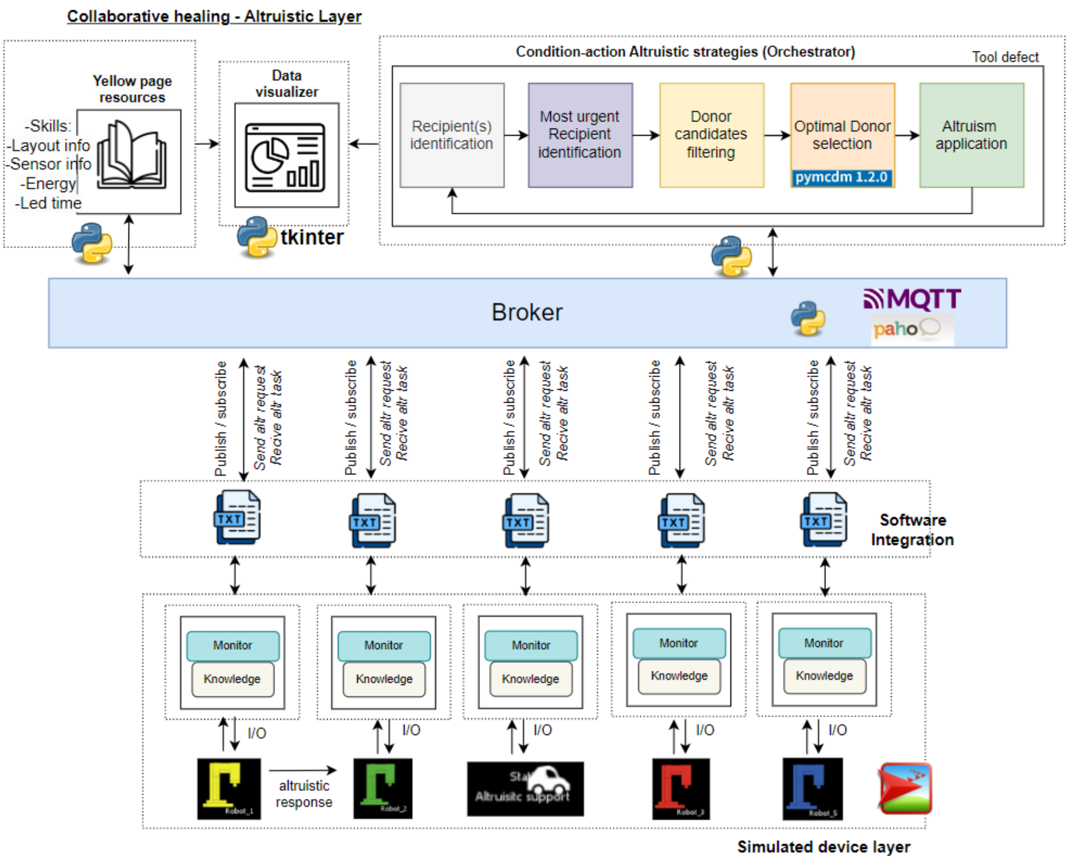


FIGURE 13. Implementation of the simulated scenario.

TABLE 4. Specific process parameters for the simulated scenario where R1's tool presents a failure.

Robot	Application	Payload(u)	Tool condition(%)	Allowed tool condition(%)	Due time(u)	dist (u)
R1	pick & place	1.0	50	80	5	32
R2	pick & place	1.2	93	80	5	18
R3	pick & place	1.5	89	80	5	10
R4	pick & place	2.0	92	80	5	18
R5	pick & place	0.5	85	80	5	32

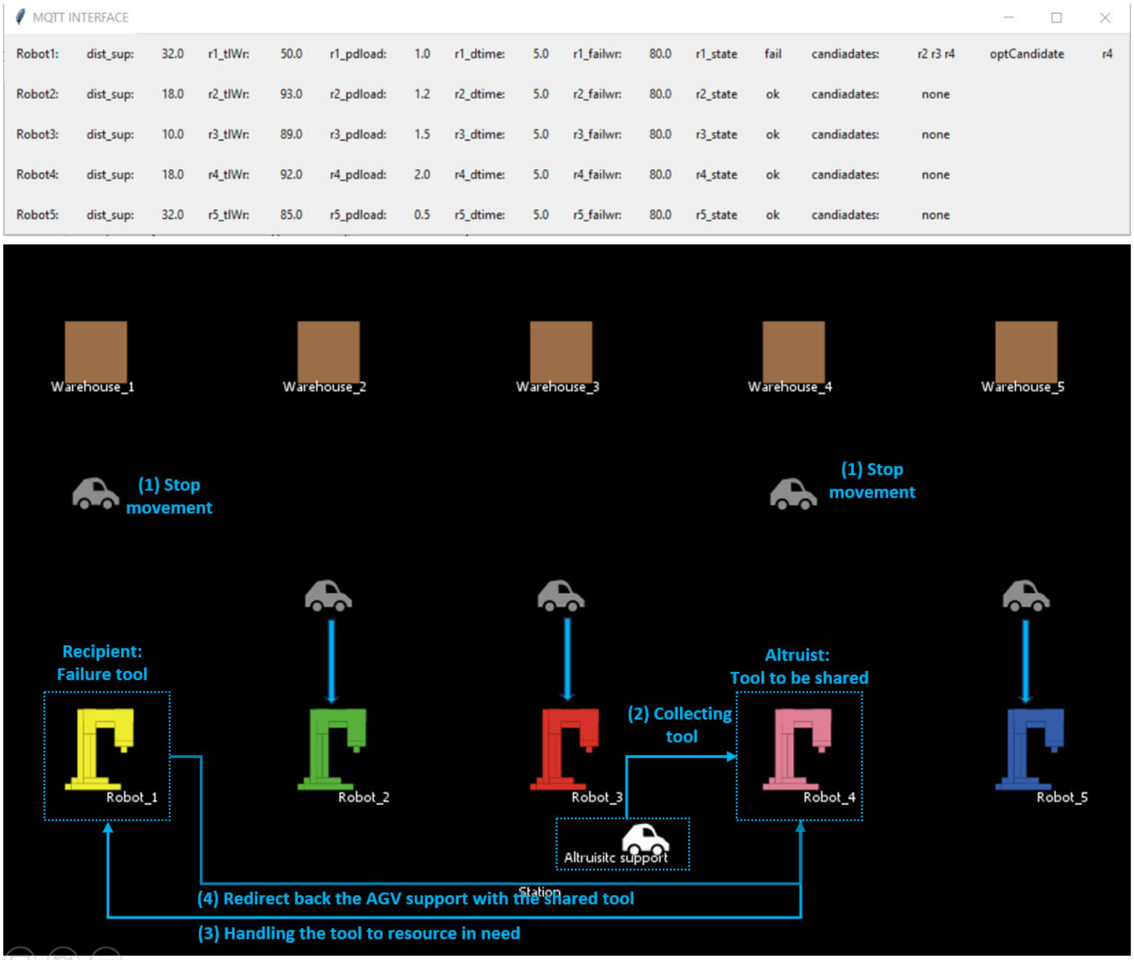


FIGURE 14. Data visualizer (upper) and validation of the concept (down).

TABLE 5. Requirements for the donor candidate in the simulated scenario.

Requirements for R1	
Application	pick & place
Payload	> 1
Allowed tool condition	> 80%

TABLE 6. Donor candidates for R1 and their parameters in the simulated scenario.

Robot	Payload (u)	Tool condition(%)	Due time(u)	dist (u)
R2	1.2	93	5	18
R3	1.5	89	5	10
R4	2.0	92	5	18

towards and from the recipient and also the processing time of the specific task the recipient robot has to fulfill. This means that the longer the processing time, the longer the downtime from the Altruistic robot. In this simulation, the sum of these variables: *downtime from the side of the recipient robot* and *downtime from the side of the Altruistic robot* is considered the *total downtime for the altruistic process*.

- In this simulation, for the case of the altruistic process we are assuming a negligible tool change time.

TABLE 7. Final score for each donor candidate, R4 has the best conditions.

	R2	R3	R4
Donor score	0.414	0.475	0.548

- The location of the altruistic support remains constant during the process.

To analyze the differences in the downtime between the altruistic and non-altruistic approaches, we generate 36 samples of data varying the processing time of a specific task, the time needed for manual tool exchange, and calculating the downtime for the recipient and donor robots in the altruistic process. This information is shown in Table 8. Also, Fig. 15 presents both results in a graphical representation.

From previous results, we can confirm that the altruistic approach represents a beneficial solution in terms of a reduction in downtime in emergencies. A variable we may need to take into consideration is the time the operator needs to make the tool exchange and the operator's reaction time. The faster the operator is, the closer the manual results could align with the altruistic ones. Similarly important is the dependence that the altruistic tool sharing has when there are longer processing times. In this case, the entity that is sharing may wait longer periods, as presented in Fig. 15. In this example, with a processing time of 500 units, the manual process could overcome the altruistic one, because the waiting time of the altruistic robot is long. Therefore, it becomes essential to understand the conditions in which the altruistic process can be used. It is possible that a decision-making entity could facilitate this and initiate a manual tool exchange when it deems it to be more beneficial.

E. PRODUCTION RATE COMPARISON BETWEEN ALTRUISTIC OPERATIONS (AUTOMATIC) AND NON-ALTRUISTIC ONES (MANUAL)

This subsection aims to extend the findings from the scenario presented in section V-C, trying to understand the advantages and constraints of the concept in relation to production rate by contrasting the altruistic (automatic) approach with the non-altruistic approach (manual operation).

Similar to the downtime comparison, we have established several assumptions and prerequisites for the sake of simulation, enabling the acquisition of measurable results. These assumptions are presented in Table 9. Furthermore, we focus on production measurements from only two robots, the altruistic (R1) and non-altruistic (R4), as they directly impact the rate of change.

Considering these conditions and the parameters presented, we try to establish a production rate comparison comparing both scenarios (altruistic and non-altruistic). The formulation of the production rate is described in eq. (5).

$$Q = \frac{P}{T} \tag{5}$$

where:

$$\begin{aligned} Q &: \text{Production rate} \\ P &: \text{Total number of products manufactured} \\ T &: \text{Total production time} \end{aligned}$$

The total production time T is formulated as described in eq. (6)

$$T = T_{\text{av}} + T_{\text{downtime}} \tag{6}$$

where:

$$\begin{aligned} T_{\text{av}} &: \text{Time of machine availability} \\ T_{\text{downtime}} &: \text{Time of downtime} \end{aligned}$$

There is a direct relation between the production rate and the total production time in both scenarios (altruistic and non-altruistic) as the objective is to produce the same amount of products. Thus, we use the ratio presented in eq. 7 to evaluate the performance of the altruistic process under the conditions established.

$$r = \frac{T_{nonaltruistic} - T_{altruistic}}{T_{nonaltruistic}} \cdot 100 \tag{7}$$

where:

$$\begin{aligned} r &: \text{Production rate comparison} \\ T_{\text{non altruistic}} &: \text{Total time under non-altruistic conditions} \\ T_{\text{altruistic}} &: \text{Total time under altruistic conditions} \end{aligned}$$

These formulations and conditions allow us to calculate the results presented in Table 10.

As expected, the results obtained show a slight improvement in the production rate of an altruistic process when compared to a non-altruistic one. This was expected as the previous subsection shows a decrease in the production downtime. The same results show the dependency on the processing time as it may decrease the production rate when using the altruistic strategy (as the total time needed could be longer due to longer waiting times). For example, in the case of sample 6 (0.05% decrement in production comparing the altruistic with the manual approach). It should be highlighted that these values should be used as a reference as they are dependent on specific conditions such as the percentage of emergencies, the number of products that are being produced, and even the layout of the shop floor.

VI. LIMITATIONS AND FUTURE WORKS

From the idea and proof of concept presented in this paper, several lines of research can be expanded and elaborated.

- *Assessment of altruism need:* The evaluation of the conditions on which an altruistic strategy makes sense needs to be considered especially when a manual alternative can be more effective in terms of downtime and as shown in the preliminary results provided in this work. A first consideration is a decision-making entity that could facilitate this and launch different

TABLE 8. Downtime comparison between non-altruistic and altruistic process.

	Non-Altruistic Process (Manual)				Altruistic Process (Automatic)		
Sample	Processing time(u)	Time for manual tool exchange(u)	Operator preparation and reaction time(u)	Total downtime for manual operations(u)	Down time of Recipient Robot(u)	Down time of Altruistic Robot(u)	Total downtime for altruistic process(u)
1	10,0	30,0	600,0	**630,0**	62,7	132,4	**195,1**
2	30,0	30,0	600,0	**630,0**	62,7	152,4	**215,1**
3	60,0	30,0	600,0	**630,0**	62,7	182,4	**245,1**
4	100,0	30,0	600,0	**630,0**	62,7	222,4	**285,1**
5	300,0	30,0	600,0	**630,0**	62,7	422,4	**485,1**
6	500,0	30,0	600,0	**630,0**	62,7	622,4	**685,1**
7	10,0	60,0	600,0	**660,0**	62,7	132,4	**195,1**
8	30,0	60,0	600,0	**660,0**	62,7	152,4	**215,1**
9	60,0	60,0	600,0	**660,0**	62,7	182,4	**245,1**
10	100,0	60,0	600,0	**660,0**	62,7	222,4	**285,1**
11	300,0	60,0	600,0	**660,0**	62,7	422,4	**485,1**
12	500,0	60,0	600,0	**660,0**	62,7	622,4	**685,1**
13	10,0	90,0	600,0	**690,0**	62,7	132,4	**195,1**
14	30,0	90,0	600,0	**690,0**	62,7	152,4	**215,1**
15	60,0	90,0	600,0	**690,0**	62,7	182,4	**245,1**
16	100,0	90,0	600,0	**690,0**	62,7	222,4	**285,1**
17	300,0	90,0	600,0	**690,0**	62,7	422,4	**485,1**
18	500,0	90,0	600,0	**690,0**	62,7	622,4	**685,1**
19	10,0	120,0	600,0	**720,0**	62,7	132,4	**195,1**
20	30,0	120,0	600,0	**720,0**	62,7	152,4	**215,1**
21	60,0	120,0	600,0	**720,0**	62,7	182,4	**245,1**
22	100,0	120,0	600,0	**720,0**	62,7	222,4	**285,1**
23	300,0	120,0	600,0	**720,0**	62,7	422,4	**485,1**
24	500,0	120,0	600,0	**720,0**	62,7	622,4	**685,1**
25	10,0	150,0	600,0	**750,0**	62,7	132,4	**195,1**
26	30,0	150,0	600,0	**750,0**	62,7	152,4	**215,1**
27	60,0	150,0	600,0	**750,0**	62,7	182,4	**245,1**
28	100,0	150,0	600,0	**750,0**	62,7	222,4	**285,1**
29	300,0	150,0	600,0	**750,0**	62,7	422,4	**485,1**
30	500,0	150,0	600,0	**750,0**	62,7	622,4	**685,1**
31	10,0	300,0	600,0	**900,0**	62,7	132,4	**195,1**
32	30,0	300,0	600,0	**900,0**	62,7	152,4	**215,1**
33	60,0	300,0	600,0	**900,0**	62,7	182,4	**245,1**
34	100,0	300,0	600,0	**900,0**	62,7	222,4	**285,1**
35	300,0	300,0	600,0	**900,0**	62,7	422,4	**485,1**
36	500,0	300,0	600,0	**900,0**	62,7	622,4	**685,1**

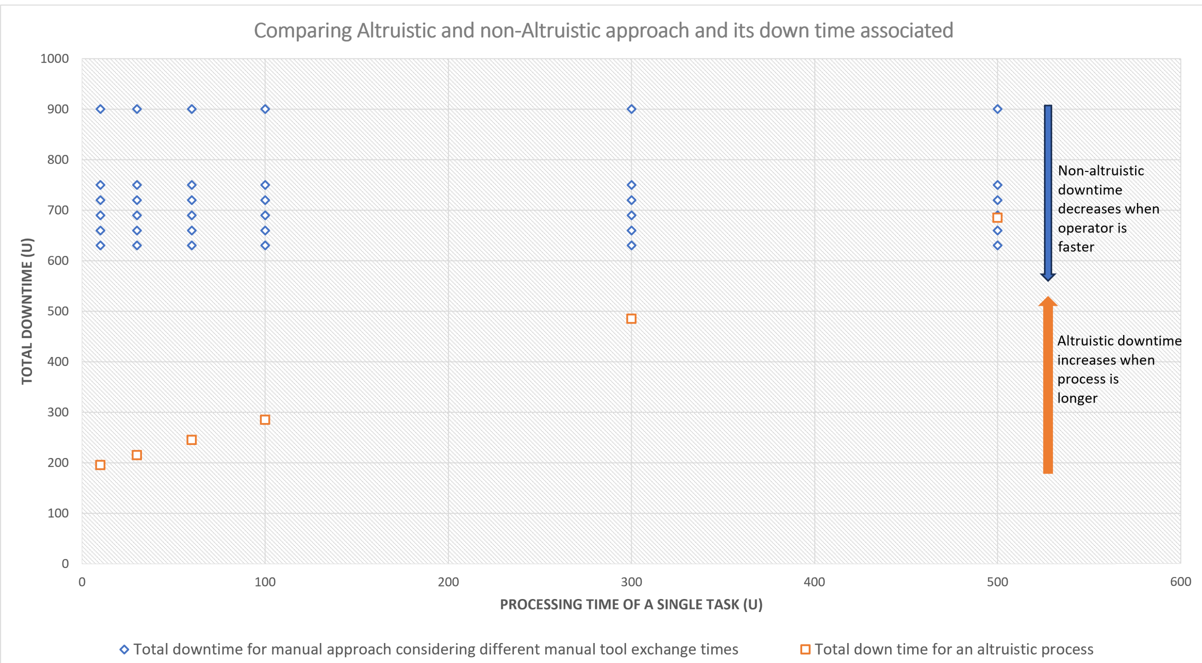


FIGURE 15. Comparing Altruistic and non-Altruistic approach and its downtime associated.

TABLE 9. Assumptions for the production rate comparison between an Altruistic and a non-Altruistic approach.

Assumptions for the simulation	
Percentage of emergency situations	1%
Number of products per robot	100
Handling time of a single product	49,72s

strategies (altruistic or non-altruistic ones) according to the parameters and conditions of the problem.

- *Elaboration of altruistic strategies (in terms of application):* To understand the full potential of the altruistic concept, it is necessary to elaborate and evaluate other scenarios (control logic, proof of concepts, etc.) in terms of applications, e.g., energy sharing or load sharing. The awareness generated from these results can be a source to generalize the idea of this paper with more details. Preliminary work in this direction has been already published by the authors considering the case of a peer-to-peer energy-sharing solution [67]. However, these concepts should be further elaborated.
- *Availability of current technological enablers:* While we believe the idea presented in this work is promising, it is important to recognize the limitations that current technological enablers may have to exploit the full potential of the concept of altruism applied in real scenarios. One example to consider is the energy-sharing application, where the sole energy transference may take a considerable amount of time, being a source of downtime when considering altruism. Therefore, the strategies designed need to be able to cope with current technological limitations.
- *Multi-objective altruistic strategy:* In many cases, when an altruistic strategy can be used, there could be more than one strategy that can be applied. We started by filtering an "optimal" candidate in terms of its parameters in this work, but other considerations could be done as well, e.g., considering the optimization of the transportation time, providing variability in terms of the speed of movement of the AGV support, etc. This will undoubtedly increase the complexity of the problem but will be necessary if more optimal and real conditions want to be achieved.
- *Indirect communication based on signal perception*: In future iterations, exploring a decentralized communication infrastructure—replacing the broker—with a system based on perception signals, akin to natural (bat) communication without a digital connection bus, presents an intriguing direction. One initial concept involves generating broadcasting signals initiated by Recipient resources. Potential receivers of these signals could be considered as Donor(s).
- *Human in the loop:* Despite automation and advanced technologies, humans play a crucial and active role in a collaborative system. Humans are pivotal in decision-making, problem-solving, and contributing to the holistic functioning of the system [54]. Operators interact with technology, machines, and other resources and can provide insights based on experience, and feedback on system performance, and contribute to the evolution of processes for better efficiency and effectiveness. This collaborative integration seeks to optimize the synergy between human intelligence and technological advancements, fostering more efficient collaborative grounded manufacturing processes. Hence, integrating humans into the framework with the necessary and appropriate modifications, and systematically tracking the outcomes, presents a prospective road for steering the future direction of extending the framework.

Further iterations of this work will try to address these challenges. Also, a lab experiment is planned using several educational robotic platforms namely the Turtlebot3 at the UNINOVA Institute.

VII. CONCLUSION

In this work, we have addressed the study of a novel approach for collaborative healing behavior of manufacturing resources based on the concept of altruism performed by some animal species, i.e., vampire bats. This idea has been conceptualized by the provision of two roles: Altruistic/Donors and Recipients. Also, the idea has been formalized using a broker and a publish-subscribe mechanism as a tool for information exchange.

The initial implementation of the framework focused on the application of tool sharing of robots in the case of a tool failure. The solution was deployed using an MQTT broker and Netlogo as the shop-floor simulator. The framework was also capable of recognizing which donor candidate has the optimal support "conditions" using multi-criteria decision-making.

From the tests performed in this work based on downtime measurement and production rate comparison, when applying a non-altruistic (manual) and an altruistic (automatic) approach, it was possible to observe that generally, the altruistic outperforms the non-altruistic one. This is shown in sample 1 (Table 8). For a minimum processing time, the downtime is drastically reduced when having an altruistic approach (almost 3 times). For sample 12 (high processing time), there is a slight increase in downtime for the altruistic approach.

For sample 31 (Table 10) it is possible to see an increase of more than 5% in the production rate when applying an altruistic approach (reduced processing time), while for sample 6 (high processing time), the production rate is slightly reduced when applying the altruistic approach (around 0.05%).

This validates the importance of the concept for self-organized healing/maintenance tasks, and being an interesting alternative for failures that cannot be predicted and emergencies in the shop floor. Naturally, this concept has to be developed and evaluated to understand in which conditions

TABLE 10. Production-rate comparison between non-altruistic and altruistic process for R1 and R4 (x100 products) (highlighting max and min production rate).

Sample	Processing time of a single product(u)	Total time of availability(u)	Downtime associated in the manual processes(u)	Total production time in the manual process(u)	Downtime in the altruistic process(u)	Total production time with the altruistic process(u)	Production rate comparison (%)
1	10,0	11944,0	**630,0**	12574,0	**195,1**	12139,1	**3,46**
2	30,0	15944,0	**630,0**	16574,0	**215,1**	16159,1	**2,50**
3	60,0	21944,0	**630,0**	22574,0	**245,1**	22189,1	**1,71**
4	100,0	29944,0	**630,0**	30574,0	**285,1**	30229,1	**1,13**
5	300,0	69944,0	**630,0**	70574,0	**485,1**	70429,1	**0,21**
6	500,0	109944,0	**630,0**	110574,0	**685,1**	110629,1	**-0,05**
7	10,0	11944,0	**660,0**	12604,0	**195,1**	12139,1	**3,69**
8	30,0	15944,0	**660,0**	16604,0	**215,1**	16159,1	**2,68**
9	60,0	21944,0	**660,0**	22604,0	**245,1**	22189,1	**1,84**
10	100,0	29944,0	**660,0**	30604,0	**285,1**	30229,1	**1,23**
11	300,0	69944,0	**660,0**	70604,0	**485,1**	70429,1	**0,25**
12	500,0	109944,0	**660,0**	110604,0	**685,1**	110629,1	**-0,02**
13	10,0	11944,0	**690,0**	12634,0	**195,1**	12139,1	**3,92**
14	30,0	15944,0	**690,0**	16634,0	**215,1**	16159,1	**2,85**
15	60,0	21944,0	**690,0**	22634,0	**245,1**	22189,1	**1,97**
16	100,0	29944,0	**690,0**	30636,0	**285,1**	30229,1	**1,32**
17	300,0	69944,0	**690,0**	70634,0	**485,1**	70429,1	**0,29**
18	500,0	109944,0	**690,0**	110634,0	**685,1**	110629,1	**0**
19	10,0	11944,0	**720,0**	12664,0	**195,1**	12139,1	**4,14**
20	30,0	15944,0	**720,0**	16664,0	**215,1**	16159,1	**3,03**
21	60,0	21944,0	**720,0**	22664,0	**245,1**	22189,1	**2,10**
22	100,0	29944,0	**720,0**	30664,0	**285,1**	30229,1	**1,42**
23	300,0	69944,0	**720,0**	70664,0	**485,1**	70429,1	**0,33**
24	500,0	109944,0	**720,0**	110664,0	**685,1**	110629,1	**0,03**
25	10,0	11944,0	**750,0**	12694,0	**195,1**	12139,1	**4,37**
26	30,0	15944,0	**750,0**	16694,0	**215,1**	16159,1	**3,20**
27	60,0	21944,0	**750,0**	22694,0	**245,1**	22189,1	**2,22**
28	100,0	29944,0	**750,0**	30694,0	**285,1**	30229,1	**1,51**
29	300,0	69944,0	**750,0**	70694,0	**485,1**	70429,1	**0,37**
30	500,0	109944,0	**750,0**	110694,0	**685,1**	110629,1	**0,06**
31	10,0	11944,0	**900,0**	12844,0	**195,1**	12139,1	**5,49**
32	30,0	15944,0	**900,0**	16844,0	**215,1**	16159,1	**4,07**
33	60,0	21944,0	**900,0**	22844,0	**245,1**	22189,1	**2,87**
34	100,0	29944,0	**900,0**	30844,0	**285,1**	30229,1	**1,99**
35	300,0	69944,0	**900,0**	70844,0	**485,1**	70429,1	**0,59**
36	500,0	109944,0	**900,0**	110844,0	**685,1**	110629,1	**0,19**

an altruistic approach is justified as explained in section VI of this work.

It is also important to highlight the role of Artificial Intelligence techniques for two key reasons. Firstly, this approach forms a distributed system composed of autonomous entities capable of independent communication about their needs. Secondly, owing to their self-awareness, these entities can detect failures and then communicate their requirements.

Finally, we believe these findings highlight how bio-inspired solutions can help tackle the persistent challenges in smart manufacturing, especially in engineering design, and hope can inspire new ideas in the field.

ACKNOWLEDGMENT

The authors would like to thank Nathaly Rea (Royal Institute of Technology) and Francisco Marques (UNINOVA) for sharing their pearls of wisdom during the development of this research. Icons used in certain figures were provided by www.flaticon.com

REFERENCES

[1] E. Oztemel and S. Gursev, "Literature review of industry 4.0 and related technologies," *J. Intell. Manuf.*, vol. 31, no. 1, pp. 127–182, Jan. 2020.

[2] H. Van Brussel, J. Wyns, P. Valckenaers, L. Bongaerts, and P. Peeters, "Reference architecture for holonic manufacturing systems: PROSA," *Comput. Ind.*, vol. 37, no. 3, pp. 255–274, Nov. 1998.

[3] P. Leitão and F. Restivo, "ADACOR: A holonic architecture for agile and adaptive manufacturing control," *Comput. Ind.*, vol. 57, no. 2, pp. 121–130, Feb. 2006.

[4] J. Barata and L. M. Camarinha-Matos, "Coalitions of manufacturing components for shop floor agility-the cobasa architecture," *Int. J. Netw. Virtual Organisations*, vol. 2, no. 1, pp. 50–77, 2003.

[5] M. Onori, N. Lohse, J. Barata, and C. Hanisch, "The IDEAS project: Plug & produce at shop-floor level," *Assem. Autom.*, vol. 32, no. 2, pp. 124–134, Apr. 2012.

[6] A. Tharumarajah, "Comparison of the bionic, fractal and holonic manufacturing system concepts," *Int. J. Comput. Integr. Manuf.*, vol. 9, no. 3, pp. 217–226, Jan. 1996.

[7] G. Byrne, D. Dimitrov, L. Monostori, R. Teti, F. van Houten, and R. Wertheim, "Biologicalisation: Biological transformation in manufacturing," *CIRP J. Manuf. Sci. Technol.*, vol. 21, pp. 1–32, May 2018.

[8] K. Wegener, O. Damm, S. Harst, S. Ihlenfeldt, L. Monostori, R. Teti, R. Wertheim, and G. Byrne, "Biologicalisation in manufacturing—Current state and future trends," *CIRP Ann.*, vol. 72, no. 2, pp. 781–807, 2023.

[9] L. A. Estrada-Jimenez, T. Pulikottil, S. Nikghadam-Hojjati, and J. Barata, "Self-organization in smart manufacturing—Background, systematic review, challenges and outlook," *IEEE Access*, vol. 11, pp. 10107–10136, 2023.

[10] P. Leitão, J. Queiroz, and L. Sakurada, "Collective intelligence in self-organized industrial cyber-physical systems," *Electronics*, vol. 11, no. 19, p. 3213, Oct. 2022.

[11] Á. Bányai, B. Illés, E. Glistau, N. I. C. Machado, P. Tamás, F. Manzoor, and T. Bányai, "Smart cyber-physical manufacturing: Extended and real-time optimization of logistics resources in matrix production," *Appl. Sci.*, vol. 9, no. 7, p. 1287, Mar. 2019.

[12] KUKA. *Matrix Production: An Example for Industrie 4.0.* Accessed: Apr. 4, 2022. [Online]. Available: https://www.kuka.com/en-de/industries/solutions-database/2016/10/matrix-production

[13] R. Berger. *Rise of the Machines—How Robots and Artificial Intelligence Are Shaping the Future of Autonomous Production*. Accessed: Apr. 4, 2022. [Online]. Available: https://www.rolandberger.com/en/Insights/Publications/Autonomous-production-Rise-of-the-machines.html

[14] G. Fragapane, R. de Koster, F. Sgarbossa, and J. O. Strandhagen, "Planning and control of autonomous mobile robots for intralogistics: Literature review and research agenda," *Eur. J. Oper. Res.*, vol. 294, no. 2, pp. 405–426, Oct. 2021.

[15] A. Malshe, S. Bapat, K. Rajurkar, and S. Melkote, "Biological strategies from natural structures for resilience in manufacturing," *CIRP J. Manuf. Sci. Technol.*, vol. 34, pp. 146–156, Aug. 2021.

[16] M. Onori, "Evolvable assembly systems—A new paradigm?" in *Proc. 33rd Int. Symp. Robot. (ISR)*, Stockholm, Sweden, 2002, pp. 617–621.

[17] M. Abid, S. Ayub, H. Wali, and M. N. Tariq, "Reliability centered maintenance plan for the utility section of a fertilizer industry: A case study," *Int. J. Sci. Adv. Technol.*, vol. 4, no. 3, pp. 9–16, 2014.

[18] D. C. Brauer and G. D. Brauer, "Reliability-centered maintenance," *IEEE Trans. Rel.*, vol. R-36, no. 1, pp. 17–24, Apr. 1987.

[19] J. Dias-Ferreira, L. Ribeiro, H. Akillioglu, P. Neves, and M. Onori, "BIOSOARM: A bio-inspired self-organising architecture for manufacturing cyber-physical shopfloors," *J. Intell. Manuf.*, vol. 29, no. 7, pp. 1659–1682, Oct. 2018.

[20] A. D. Rocha, P. Lima-Monteiro, M. Parreira-Rocha, and J. Barata, "Artificial immune systems based multi-agent architecture to perform distributed diagnosis," *J. Intell. Manuf.*, vol. 30, no. 4, pp. 2025–2037, Apr. 2019.

[21] L. Wang, C. Luo, J. Cai, and M. Li, "An efficient agent-based biological immune system approach to adaptive manufacturing system control," *Int. J. Robot. Autom.*, vol. 32, no. 1, pp. 78–86, 2017.

[22] T. Pulikottil, L. A. Estrada-Jimenez, and J. Barata, "Conceptual framework for smart maintenance based on distributed intelligence," *IFAC-PapersOnLine*, vol. 55, no. 19, pp. 121–126, 2022.

[23] J. Barbosa, P. Leitão, E. Adam, and D. Trentesaux, "Dynamic self-organization in holonic multi-agent manufacturing systems: The ADACOR evolution," *Comput. Ind.*, vol. 66, pp. 99–111, Jan. 2015.

[24] A. Madureira, I. Pereira, P. Pereira, and A. Abraham, "Negotiation mechanism for self-organized scheduling system with collective intelligence," *Neurocomputing*, vol. 132, pp. 97–110, May 2014.

[25] N. H. Tran, H. S. Park, Q. V. Nguyen, and T. D. Hoang, "Development of a smart cyber-physical manufacturing system in the industry 4.0 context," *Appl. Sci.*, vol. 9, no. 16, p. 3325, Aug. 2019.

[26] B. Micieta, M. Edl, M. Krajcovic, L. Dulina, P. Bubenik, L. Durica, and V. Binasova, "Delegate MASs for coordination and control of one-directional AGV systems: A proof-of-concept," *Int. J. Adv. Manuf. Technol.*, vol. 94, nos. 1–4, pp. 415–431, Jan. 2018.

[27] A. V. Barenji and R. V. Barenji, "Improving multi-agent manufacturing control system by indirect communication based on ant agents," *Proc. Inst. Mech. Eng., I, J. Syst. Control Eng.*, vol. 231, no. 6, pp. 447–458, Jul. 2017.

[28] R. Pannequin and A. Thomas, "Another interpretation of stigmergy for product-driven systems architecture," *J. Intell. Manuf.*, vol. 23, no. 6, pp. 2587–2599, Dec. 2012.

[29] R. Ogunsakin, C. A. Marin, and N. Mehandjiev, "Towards engineering manufacturing systems for mass personalisation: A stigmergic approach," *Int. J. Comput. Integr. Manuf.*, vol. 34, no. 4, pp. 341–369, Apr. 2021.

[30] V. Charpenay, D. Schraudner, T. Seidelmann, T. Spieldenner, J. Weise, R. Schubotz, S. Mostaghim, and A. Harth, "MOSAIK: A formal model for self-organizing manufacturing systems," *IEEE Pervasive Comput.*, vol. 20, no. 1, pp. 9–18, Jan. 2021.

[31] P. Stock and G. Zülch, "Reactive manufacturing control using the ant colony approach," *Int. J. Prod. Res.*, vol. 50, no. 21, pp. 6150–6161, Nov. 2012.

[32] T. Borangiu, S. Raileanu, D. Trentesaux, T. Berger, and I. Iacob, "Distributed manufacturing control with extended CNP interaction of intelligent products," *J. Intell. Manuf.*, vol. 25, no. 5, pp. 1065–1075, Oct. 2014.

[33] F. G. Quintanilla, O. Cardin, A. L'Anton, and P. Castagna, "A modeling framework for manufacturing services in service-oriented holonic manufacturing systems," *Eng. Appl. Artif. Intell.*, vol. 55, pp. 26–36, Oct. 2016.

[34] A. Sadik and B. Urban, "Combining adaptive holonic control and ISA-95 architectures to self-organize the interaction in a worker-industrial robot cooperative workcell," *Future Internet*, vol. 9, no. 3, p. 35, Jul. 2017.

[35] H. Lee and A. Banerjee, "Executable design and control framework using reconfigurable manufacturing holons and its evolution algorithm," *Int. J. Prod. Res.*, vol. 49, no. 5, pp. 1405–1423, Mar. 2011.

[36] J.-F. Jimenez, A. Bekrar, G. Zambrano-Rey, D. Trentesaux, and P. Leitão, "Pollux: A dynamic hybrid control architecture for flexible job shop systems," *Int. J. Prod. Res.*, vol. 55, no. 15, pp. 4229–4247, Aug. 2017.

[37] D. Macherki, T. M. L. Diallo, J.-Y. Choley, A. Guizani, M. Barkallah, and M. Haddar, "QHAR: Q-holonic-based architecture for self-configuration of cyber–physical production systems," *Appl. Sci.*, vol. 11, no. 19, p. 9013, Sep. 2021.

[38] A. Martín-Gómez, M. J. Ávila-Gutiérrez, and F. Aguayo-González, "Holonic reengineering to foster sustainable cyber-physical systems design in cognitive manufacturing," *Appl. Sci.*, vol. 11, no. 7, p. 2941, Mar. 2021.

[39] R. Frei, G. Di Marzo Serugendo, and T. F. Şerbănuţă, "Ambient intelligence in self-organising assembly systems using the chemical reaction model," *J. Ambient Intell. Humanized Comput.*, vol. 1, no. 3, pp. 163–184, Sep. 2010.

[40] R. Frei and G. D. M. Serugendo, "Self-organizing assembly systems," *IEEE Trans. Syst., Man, Cybern., C, Appl. Rev.*, vol. 41, no. 6, pp. 885–897, Nov. 2011.

[41] N. Zbib, C. Pach, Y. Sallez, and D. Trentesaux, "Heterarchical production control in manufacturing systems using the potential fields concept," *J. Intell. Manuf.*, vol. 23, no. 5, pp. 1649–1670, Oct. 2012.

[42] M. O. F. Sarker, T. S. Dahl, E. Arcaute, and K. Christensen, "Local interactions over global broadcasts for improved task allocation in self-organized multi-robot systems," *Robot. Auto. Syst.*, vol. 62, no. 10, pp. 1453–1462, Oct. 2014.

[43] P. Leitão, J. Barbosa, and D. Trentesaux, "Bio-inspired multi-agent systems for reconfigurable manufacturing systems," *Eng. Appl. Artif. Intell.*, vol. 25, no. 5, pp. 934–944, Aug. 2012.

[44] C. Pach, T. Berger, T. Bonte, and D. Trentesaux, "ORCA-FMS: A dynamic architecture for the optimized and reactive control of flexible manufacturing scheduling," *Comput. Ind.*, vol. 65, no. 4, pp. 706–720, May 2014.

[45] R. L. Trivers, "The evolution of reciprocal altruism," *Quart. Rev. Biol.*, vol. 46, no. 1, pp. 35–57, Mar. 1971.

[46] M. Vuorensyrjä, "The rise of reciprocal altruism—A theory based on the centipede game with trivers-payoffs," *Evol. Psychol. Sci.*, vol. 9, no. 1, pp. 13–25, May 2022.

[47] D. Örtqvist, "Performance outcomes from reciprocal altruism: A multi-level model," *J. Small Bus. Entrepreneurship*, vol. 32, no. 3, pp. 227–240, May 2020.

[48] M. Arman, "Empathy, sympathy, and altruism—An evident triad based on compassion. A theoretical model for caring," *Scandin. J. Caring Sci.*, vol. 37, no. 3, pp. 862–871, Sep. 2023.

[49] R. Mouser, "Mutual aid as effective altruism," *Kennedy Inst. Ethics J.*, vol. 33, no. 2, pp. 201–226, Jun. 2023.

[50] B. Berkey, "The philosophical core of effective altruism," *J. Social Philosophy*, vol. 52, no. 1, pp. 92–113, Mar. 2021.

[51] G. Roberts, "Cooperation: How vampire bats build reciprocal relationships," *Current Biol.*, vol. 30, no. 7, pp. R307–R309, Apr. 2020.

[52] R. Layton, "Kinship without words," *Biol. Theory*, vol. 16, no. 3, pp. 135–147, Sep. 2021.

[53] S. Hirata, "Collaborative behavior," in *Encyclopedia of Animal Behavior*, J. C. Choe, Ed., 2nd ed. Oxford, U.K.: Academic, 2019, pp. 343–348.

[54] S. Kalateh, L. A. Estrada-Jimenez, T. Pulikottil, S. N. Hojjati, and J. Barata, "The human role in human-centric industry," in *Proc. 48th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2022, pp. 1–6.

[55] G. S. Wilkinson, "Reciprocal altruism in bats and other mammals," *Ethol. Sociobiol.*, vol. 9, nos. 2–4, pp. 85–100, Jul. 1988.

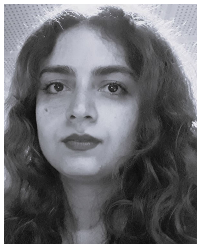
[56] E. Aloyo, "Effective altruism, tithing, and a principle of progressive giving," *Ethics Global Politics*, vol. 16, no. 3, pp. 20–34, Jul. 2023.

[57] K. Ding, F. T. S. Chan, X. Zhang, G. Zhou, and F. Zhang, "Defining a digital twin-based cyber-physical production system for autonomous manufacturing in smart shop floors," *Int. J. Prod. Res.*, vol. 57, no. 20, pp. 6315–6334, Oct. 2019.

[58] L. A. E. Jimenez, D. Sanderson, J. C. Chaplin, and J. Barata, "Self-configuration of a robotic platform to support a self-organized manufacturing process," in *Proc. 48th Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2022, pp. 1–6.

[59] S. Wang, J. Wan, D. Zhang, D. Li, and C. Zhang, "Towards smart factory for industry 4.0: A self-organized multi-agent system with big data based feedback and coordination," *Comput. Netw.*, vol. 101, pp. 158–168, Jun. 2016.
[60] A. Maeedi, M. U. Khan, and B. Irfanoglu, "Reciprocal altruism-based path planning optimization for multi-agents," in *Proc. Int. Congr. Hum.-Comput. Interact., Optim. Robot. Appl. (HORA)*, Jun. 2022, pp. 1–9.
[61] H. Tang, D. Li, J. Wan, M. Imran, and M. Shoaib, "A reconfigurable method for intelligent manufacturing based on industrial cloud and edge intelligence," *IEEE Internet Things J.*, vol. 7, no. 5, pp. 4248–4259, May 2020.
[62] A. Shojaeinasab, T. Charter, M. Jalayer, M. Khadivi, O. Ogunfowora, N. Raiyani, M. Yaghoubi, and H. Najjaran, "Intelligent manufacturing execution systems: A systematic review," *J. Manuf. Syst.*, vol. 62, pp. 503–522, Jan. 2022.
[63] B. Anuraj, "Agent-based orchestration on a swarm of edge devices," in *Proc. 17th ACM Int. Conf. Distrib. Event-Based Syst.*, Jun. 2023, pp. 199–202.
[64] H. Taherdoost and M. Madanchian, "Multi-criteria decision making (MCDM) methods and concepts," *Encyclopedia*, vol. 3, no. 1, pp. 77–87, Jan. 2023.
[65] S. Chakraborty, "TOPSIS and modified TOPSIS: A comparative analysis," *Decis. Anal. J.*, vol. 2, Mar. 2022, Art. no. 100021.
[66] B. Kizielewicz, A. Shekhovtsov, and W. Sałabun, "Pymcdm—The universal library for solving multi-criteria decision-making problems," *SoftwareX*, vol. 22, Jan. 2023, Art. no. 101368.
[67] L. A. Estrada-Jimenez, S. Kalateh, S. N. Hojjati, and J. Barata, "A bio-inspired and altruistic-based framework to support collaborative healing in a smart manufacturing shop-floor," in *Proc. Doctoral Conf. Comput., Elect. Ind. Syst.* Cham, Switzerland: Springer, 2023, pp. 111–121.

LUIS A. ESTRADA-JIMENEZ received the B.Sc. degree in electronic and control engineering from Escuela Politecnica Nacional, Ecuador, in 2016, and the M.Sc. degree in mechatronics engineering from the University of Oviedo, Spain, in 2019. He is currently pursuing the Ph.D. degree in electrical and computer engineering with the Nova University of Lisbon, Portugal. His master's thesis was developed at the company FESTO, Germany, Department of Modular Automation. He is also with Instituto de Desenvolvimento de Novas Tecnologias (UNINOVA). His main role right now is as an Early Stage Researcher with the Digital Manufacturing and Design Training Network (DIMAND), funded by the European Union. His research interests include self-organization and automation in smart manufacturing systems and the application of artificial intelligence in industrial environments.



SEPIDEH KALATEH received the B.Sc. degree in electronic and electrical engineering and the M.Sc. degree in information technology management from IAU, Iran, in 2012 and 2017, respectively. She is currently pursuing the Ph.D. degree in electrical and computer engineering with Nova University Lisbon, Portugal. She is also a Researcher with Instituto de Desenvolvimento de Novas Tecnologias (UNINOVA). With a professional experiences in various industrial sectors alongside her academic background, including ICT and data management, her research interests include affective computing, computational creativity, and data science in the field of human–machine affective interaction.

SANAZ NIKGHADAM-HOJJATI (Member, IEEE) received the Ph.D. degree in information technology management (business intelligence) from IAU, in 2017. She is currently a Senior Researcher with Instituto de Desenvolvimento de Novas Tecnologias (UNINOVA), Nova University of Lisbon. From 2018 to 2019, she was a Postdoctoral Researcher with the Nova School of Science and Technology, Nova University of Lisbon. Her research interests include computational creativity, affective computing, business intelligence, human behavior, and emerging technologies, ICT, and innovation management. She has published several books and academic papers in a number of peer-reviewed journals and presented various academic papers at conferences. She has led and participated in several European Union projects, Portuguese, and Iranian National projects. In addition, she was a University Invited Professor, and also she is the Director of the Women in Science, Technology, Engineering, and Mathematics (WoSTEM) Program, UNINOVA.

JOSÉ BARATA (Member, IEEE) received the Ph.D. degree in robotics and integrated manufacturing from the NOVA University of Lisbon, in 2004. He is currently a Professor with the Department of Electrical Engineering, NOVA University of Lisbon, and a Senior Researcher with Instituto de Desenvolvimento de Novas Tecnologias (UNINOVA). He has participated in more than 15 international research projects involving different programs, including NMP, IST, ITEA, and ESPRIT. Since 2004, he has been leading the UNINOVA participation in EU projects, namely, EUPASS, self-learning, IDEAS, PRIME, RIVERWATCH, ROBO-PARTNER and PROSECO. In the last years, he has participated actively researching SOA-based approaches for the implementation of intelligent manufacturing devices, such as within the Inlife Project. He has authored or coauthored over 100 original papers in international journals and international conferences. His main research interests include intelligent manufacturing, with an emphasis on complex adaptive systems, involving intelligent manufacturing devices. He is a member of the IEEE Technical Committee on Industrial Agents (IES), Self-Organization and Cybernetics for Informatics (SMC), and Education in Engineering and Industrial Technologies (IES).