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A SURVEY ON BIO-INSPIRED MULTI-AGENT SYSTEM FOR VERSATILE MANUFACTURING ASSEMBLY LINE

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Abstract. *Manufacturing industry has evolved in the past few years, due to global competitive economy, market demands for high quality and customized products, and meeting lowest possible costs. However, establishing effective manufacturing assembly line operations, in a dynamic manufacturing setting is essentially dependent upon optimum resource utilization while fulfilling various constraints and requirements. Consequently, balancing the resources in the assembly line is a complex combinatorial problem, which if not efficiently managed, may entail significant costs. As such, to facilitate the nature of the assembly line in manufacturing, a new methodology is needed. Bio-inspired methods have been popularly adopted in assembly line where several real-world problems have been successfully solved. Distributed and autonomous paradigm offered by the multi-agent system (MAS) is conducive for addressing the complexity of the manufacturing assembly line. As MAS lacks a self-organization aspect, integration of bio-inspired methods within the MAS paradigm are envisioned, where adaptive and self-organization characteristics are the key ingredients to promote robustness; thus creating a potentially self-reliant and versatile manufacturing environment.*
Keywords: Assembly line, Bio-inspired method, Multi-agent system

1. **Introduction.** The manufacturing industry has faced considerable changes in the past few years, relatively from the local economy towards a highly competitive global economy. These circumstances invoke demand for high quality customizable products at the lowest possible cost with the shortest life cycles [1]. This imposes new requirements for the manufacturing enterprises to meet in order to remain competitive and sustain the business. The assembly is considered one of the most important processes in manufacturing, as it consumes up to 50% of the production time and accounts for more than 20% of the total production cost [2]. According to [3], research in optimization of the assembly can be categorized based on which product development and production phase is being studied, which are product conception and design, production planning, and manufacturing processes.

The general aim in the product conception and design phase is to reduce the assembly costs by applying the design for assembly (DFA) approach in product design. In corollary, additional benefits can also be induced in terms of increased quality, reliability and shorter manufacturing time, thus shortening the product cycle and ensuring a smoother transition from prototype to production [3]. The production planning phase deals with determination of optimum sequence and location of each resource of the assembly. Solving the assembly sequence planning (ASP) problem is crucial because many assembly aspects, such as tool changes, fixture design, and assembly freedom, can be determined [3]. Assembly sequence also influences overall productivity because it signifies how fast and accurate the product can be assembled.

During the manufacturing processes stage, optimization is broadly focused on two major activities: determining the optimum automation level in assembly and assigning the assembly tasks into workstations. The former activity aims to balance the investment in an appropriate level of automation and the output, while the latter focuses on the workstation's task assignment where the workstations have equal or almost equal load [4], typically known as assembly line balancing (ALB). However, research in this phase is more focused on the ALB problem rather than optimization of automation level. The ALB problem involves deciding how to optimally delegate assembly work among the stations with respect to certain objectives [5]. The rationale of addressing the ALB problem is mainly because of its correlation with efficiency of the line, thus improving the manufacturing productivity and reducing cost which is relevant to the industry's engagement towards competitiveness amongst manufacturing enterprises, where most of the capital is invested [6].

The ALB problem is an NP-hard combinatorial optimization problem and cannot be solved in polynomial time even by using a powerful computer [3]. With regards to this matter, a suitable technique that meets the dynamic product demands as well as optimizes the performance of the ALB is required. An autonomous and distributed architecture, such as the multi-agent system (MAS), is suitable for encapsulating complex issues, such as real-time machine workloads, assembly line flow, and the production floor dynamics [7]. The agents represent physical resources, machine tools, and products or logical objects (orders or schedulers), which enable automated manufacturing control decisions by "negotiation" and "coordination", promoting adaptation to the dynamic and complex environment of the ALB.

Nevertheless, adopting MAS alone exposes it to the myopia effect, causing the distributed and autonomous agents to make local sub-optimal decisions due to partial knowledge of the cumulative problems [8]. Having a global optimal decision is important to optimizing an assembly line balance and manufacturing control. Fortunately, a bio-inspired method is capable of achieving and solving these complex problems through simple and effective ways. In addition, it provides the insight needed for adaptive systems to evolve, hence overcoming dynamic demands and uncertainty that is prevalent in the manufacturing domain. Simple and limited cognitive abilities with a small number of rules or laws are among the bio-inspired method characteristics that are capable to handle complex behavior emergence [9]. Furthermore, its self-organization principle is important as it essentially allows a system to perform self-configurations, self-maintenance, and self-optimization while addressing disturbances in the most natural manner [10].

Different state and variability conditions in the real industrial manufacturing assembly line systems prompt the corresponding ALB problem to be multifaceted [11]. Different sets of problems may be solved by different kinds of approaches, such as considering variations in objective measures, and integrating a number of features to gain a closer resemblance to real-world manufacturing assembly line. Vast numbers of studies have done to attempt to solve the ALB problem, which shows the importance of the current subject in the production research [12]. This paper, however, will survey the most recent work on the ALB problem, specifically in the past 5 years. The potential directions are explored and trends for future research are discussed.

The remainder of the document is organized as follows. Section 2 will provide reviews of the key literature of the respective ALB problem. Section 3 will underline the discussions of the potential research that could be conceived. Finally, Section 4 will summarize the outlooks and conclude the paper.

2. Assembly Line Balancing Approaches.

In general, researchers like [11, 13] have categorized the ALB problem into two major types: simple assembly line balancing (SALB) and generalized assembly line balancing (GALB). The difference between both will be reviewed and highlighted in this section. Comprehensive surveys have been conducted, and the results emphasize possible line integration [14], real-world applicability [15], complexity reduction [16], and line balancing problems in connection to other manufacturing processes [12] for future studies. Another extensive survey reviewed different sets of solution techniques and procedures, namely, exact methods [13], bounded-exact methods [12], heuristics [12, 13], and meta-heuristics [3, 12].

Installing an assembly line is a long-term decision which tends to demand large capital investments [11]. As such, it is vital that such a line is designed and balanced to work efficiently. In addition, the choice of line model defines how the workstations will be situated, direction of flows, and rules associated with it [12]. The single-model assembly line balancing (SMALB) problem, which involves manufacturing of a homogenous product on the line [5], is one of the most widely studied problems in the ALB community. Other variants of the ALB problem are the mixed-model assembly line balancing (MMALB) problem where several models are manufactured and the sequence to assemble the model units is involved in the decision process [11]; the U-shaped line balancing (UALB) problem where stations can be arranged to handle two workpieces at different positions of the line during the same cycle [11]; and their combinations, typically known as the mixed-model U-shaped assembly line balancing (MMUALB) problem [17]. The aforementioned line models are illustrated in Figure 1.

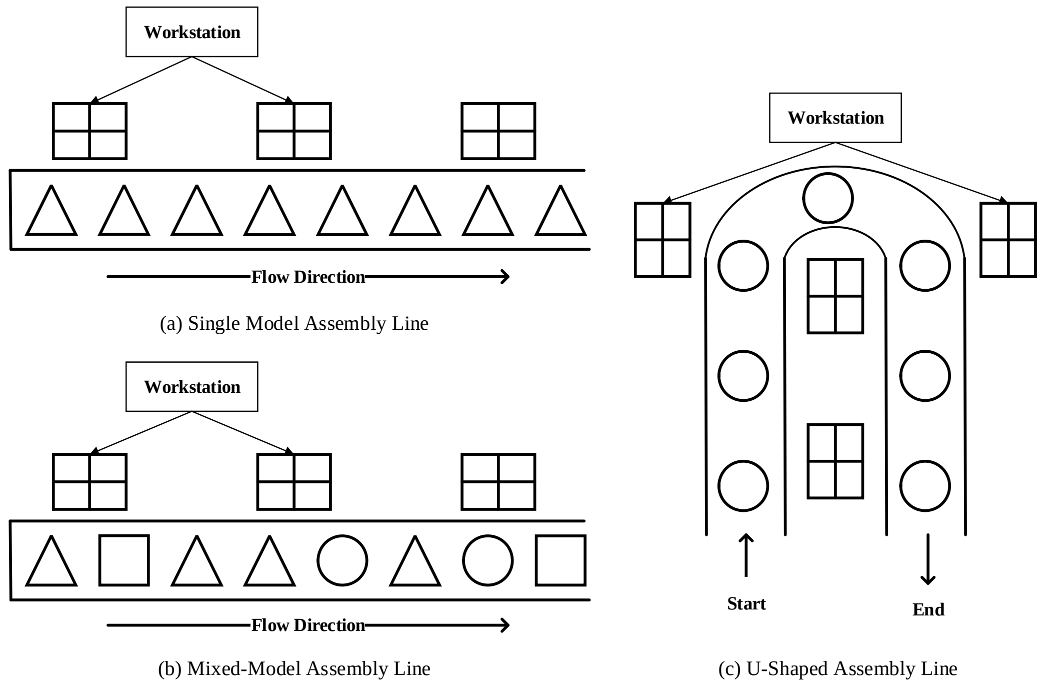

FIGURE 1. Types of line model in ALB problem

Observing recent works, two broad categorizations of the techniques and methodologies used in ALB problems are identified: exact methods and approximate methods. Exact methods, specifically mathematical techniques, are one of the most adopted techniques in solving ALB problems which seek optimum solutions [18] that applied to various scenarios from real-world problems [19]. Examples of such works are the constraint programming approach [20] for the SMALB problem, integer programming for both the SMALB problem [18] and UALB problem [19], and mixed-integer linear programming for the MMALB problem [21]. However, some works have connected ALB problems with several real industrial problems, such as station-dependent tasks [21, 22], demand uncertainty [22], workpiece positioning and task assignment restrictions [18], and multiple ergonomic restrictions [23].

Since ALB problem is NP-hard, the required computational time to obtain an optimal solution with an exact method for most of the line balancing problems increases exponentially with the size of instance considered [12]. It is clear that approximate methods are needed in order to cope with large scale cases which, although do not guarantee optimality, tend to achieve good feasible results in an acceptable computation time. Such approaches can be divided into heuristics and meta-heuristics methods.

Researchers like [24], [25], and [26] have proposed heuristic techniques to solve the SMALB, MMALB, and UALB problems, respectively. Stochastic tasks times [24, 26] and parallel stations [24] have also been incorporated. Meanwhile, another methodology that has been widely adopted is the meta-heuristic technique which is applied with respect to the meta-heuristic framework [12]. The most popular meta-heuristic techniques are genetic algorithm (GA) for SMALB problem [27] and MMALB problem [28, 29, 30]; followed by simulated annealing (SA) for UALB problem [31] and MMUALB problem [17]; and ant colony optimization (ACO) for UALB problem [32] and MMALB problem [33]. Several real-world problems are considered, namely, multiple ergonomic restrictions [17], worker allocation and assignment [17, 29], stochastic tasks times [30], re-balancing [28], and station-dependent tasks [31]. Due to several real-world problems considered in the ALB problem, an effective assembly line technique with desirable performance is vital in order to achieve well-balanced and optimum resource utilization [12]. Therefore, the need for distributed and autonomous control of the assembly line is necessary.

Multi-agent system (MAS), which can be defined as distributed control, based on autonomous agents, that account for flexible, efficient, and robust characteristics, without the need of centralized control, is a solid choice to tackle these ALB problems [34]. MAS offers an alternative way to have an adaptive complex control, where autonomous distributed entities with partial knowledge of the overall system can cooperate and adapt without needing external intervention [8]. To the best of the authors' knowledge, only one study has adopted MAS principles in handling the ALB problem [35], where MAS framework is applied and equipped with Tabu Search (TS) as the intermittent communication mechanism between two machine agents. Most agent-based manufacturing approaches, however, encounter great difficulties when applied to real-world situations because of the inability to react to uncertainties. This is essentially the ultimate problem faced in every manufacturing enterprise. The key missing ingredient is the ability to evolve and self-organize when uncertainties occur in real industrial manufacturing environments [9]. In addition, there are no existing principles on how to effectively combine the local and global knowledge of the overall system while achieving a global optimum solution without compromising the original MAS paradigm.

Analyzing how complex emergence behaviors can originate from a very simple organism offered in biological systems, can provide tremendous insight which can potentially act as a source of inspiration in order to achieve a powerful, evolvable and self-reliant mechanism needed in manufacturing systems [8, 9]. Notable biological inspirations are [1, 34]: *swarm intelligence*, where interactions between individuals lead to the emergence of "intelligent" global collective behavior; *evolutionary theory*, where nature is in the state of constant transformation between preceding generations for better adaptation to the environment; and *self-organization* where an entity/system has the ability to adapt dynamically and spontaneously according to external conditions without external intervention [36]. Therefore, bio-inspired methods have provided valuable insights needed to achieve an evolvable and self-organized manufacturing environment. Additionally, integrating self-organization, implied from the bio-inspired methods, requires a suitable distributed and decentralized architecture [1, 34, 37]. Thus, a bio-inspired method integrated with the multi-agent approach is capable of evolving and self-organizing during uncertainties which elicits potential benefits such as an efficient, responsive, and robust manufacturing assembly line.

3. **Directions and Research Opportunities.** In volatile and dynamic scenarios, where it is difficult to foresee future events, learning and adaptation can be utilized to address those dynamic environments, improving the overall performance or combined objectives of manufacturing operation. Learning capabilities contribute to the intelligence of an agent, where new knowledge and skills are acquired and can be used in the future to systematically solve problems and make better decisions [38]. Adaptation capabilities are attributable to the bio-inspired method where assembly line balancing problems can be collectively and collaboratively solved by simple means of interactions between individuals [9]. This enables the assembly line to adapt in order to respond to external changes or uncertainties (where the agent system failed due to the myopia effect), making the manufacturing line "fault-tolerant" and *robust*, thus enhancing global performance. By combining learning and adaptation to the integration of the multi-agents system and bio-inspired method, an *emergence* behavioral complex is induced, leading to evolution and self-organization towards problem solving [36, 37].

Self-organization would involve rapid exploitations of the assembly line to fundamentally satisfy the demands and requirements of a well-balanced manufacturing line. This would require some form of "awareness" and a certain degree of *communication* within that system to effectively coordinate and execute; thus enabling it to efficiently configure, maintain, and optimize the assembly line, on its own, when needed. Meanwhile, evolution of the manufacturing assembly line would underline the capacity for responsiveness, where the assembly line becomes capable of reacting when exposed to real-world environment, especially when the environment where they operate is unpredictable to a certain extent (does not involve strong real-time constraints [10]). Both self-organization and evolution within the manufacturing system are not a new approach; however, realization of these concepts is extremely rare and frequently criticized [36, 37].

Analyzing the current state-of-the-art methods from the literature, it becomes apparent that the most adopted methodology is inspired from biological systems (such as GA and ACO), mainly because of their meta-heuristic frameworks that allow near-optimal solutions to be achieved in reasonable computational time and integration of various complex restrictions and constraints. On the other hand, MAS, which has been successfully adopted into other areas of manufacturing (i.e., planning and scheduling), is rarely considered as one of the methodologies in handling ALB problem. The work in [35] integrated MAS with TS, eliciting flexibility in the assembly line with minimal developmental needs, demonstrating the potentials of other MAS integration. Therefore, the bio-inspired method which has shown the ability to provide a conducive and promising technological paradigm in handling ALB problems, would be unequivocally capable to address complex combinatorial problems of the ALB domain.

Integration of bio-inspired method with MAS highlights several potential benefits to the manufacturing domain, especially in the complexity of the ALB problems. Compared to the centralized and rigid manufacturing system, a fully autonomous and distributed manufacturing system may be achieved. For example, the expansibility of the system becomes easier (*flexible*), being only enough to modify the functioning of some agents or add new agents to the control system [38]. This enables the adoption of modular yet holistic agents, where different task specifications and constraints can be defined, allowing large and complex problem to be resolved in a simple manner. The benefits of multi-agents system also allow a new approach to the problems of ALB in manufacturing, both in the design and implementation phases, which require minimal development, debuging and maintenance [36].

4. **Outlooks and Conclusion.** Trends and directions of the literature suggest that the integration of the multi-agents system and the bio-inspired method is not only limited to the positive outcomes that can be achieved, but can also directly support the improvement

of how the manufacturing industry operates. Different variability that could be involved in the manufacturing scenarios and varieties of unpredictable parameter, demands the envisage of suitable framework to support the society of the distributed and autonomous entities, in order for the integration of multi-agents system and bio-inspired method to be beneficial. If self-organization and evolution would drive the main control and operational elements of manufacturing, the intricacy of engineering it and keeping it ubiquitous would be a major research challenge. In corollary, learning and adaptation to dynamic and often chaotic environments would highlight the requirement to overcome uncertainties (thus allowing versatility); countering the traditional "fail and recover" practices, which demands some degree of predictability in the manufacturing system.

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