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RESEARCH ARTICLE

Internet of Things-based SCADA system for configuring/reconfiguring an autonomous assembly process

Hamed Fazlollahtabar

Department of Industrial Engineering, School of Engineering, Damghan University, Damghan, Iran
Email: h.fazl@du.ac.ir

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Abstract

Industry 4.0 integrated with robotic and digital fabrication technologies have attracted the attention of manufacturing researchers. Autonomous assembly with supervisory control and data acquisition (SCADA) systems holds the promise of greater scalability, adaptability, and potentially evolved design possibilities helping to maintain efficiency, process data for smarter decisions, and communicate system issues to help mitigate downtime. This paper concerns with developing an intelligent control system based on SCADA in the Internet of Things (IoT) platform to process configuration and reconfiguration of an autonomous assembly system. The implementation study certifies the effectiveness of the proposed IoT-based SCADA control system in autonomous assembly.

1. Introduction

The advance of manufacturing technologies relates closely to information technologies (ITs). Since design and operation of a manufacturing system need numerous types of decision making at all of its levels and domains of business activities, prompt and effective decisions not only depend on reasoning techniques but also on the quality and quantity of data. Every major shifting of manufacturing paradigm has been supported by the advancement of IT. For example, the wide adoption of computer numerical control and industrial robots made flexible manufacturing systems (FMSs) feasible; the technologies for computer-aided design, computer-aided manufacturing, and computer-aided processing planning made computer-integrated manufacturing (CIM) practical. In developing their enterprise systems, more and more enterprises rely on the professional providers of IT software service to replace or advance their conventional systems [10]. Therefore, it makes sense to examine the evolution of the IT infrastructure and evaluate its impact on the evolution of manufacturing paradigms, when a new IT becomes influential.

While Internet of things (IoT) discussions often center on consumer use, there is a great potential for adoption on the manufacturing shop floor. Today's factory bears little resemblance to the stereotypical image of manufacturinLg. Long gone are the days of repetitious assembly lines where workers create part after an identical part. Today's modern shop floor is a hub of technology, full of sensors, electronic controls, and automated equipment. These interconnected devices drive efficiency, quality, and flexibility.

The vision of a smart factory is based on the notion of Industry 4.0 that denotes technologies and concepts related to cyber-physical systems (CPS) and the IoT. In smart factories, CPSs monitor physical processes, create a virtual copy of the physical world, and make decentralized decisions. Over the IoT, cyber-physical systems communicate and cooperate with each other and humans in real time. In parallel, the advancement of IoT and CPS brings some challenges to manufacturing systems. Research on manufacturing systems is focused on production scheduling [1, 4, 5], production control

[19, 20], production management [18], and other aspects of manufacturing industry. And manufacturing systems reveal increasing characteristics of discretization, intelligence, and autonomy. With the complication of manufacturing systems, it becomes very difficult to realize these characteristics by traditional technologies.

Robots today perform the mechanical assembly of various products that are typically repetitive and/or require precision component mating. The set-up of the robot(s) and the automated assembly flow process necessitate extensive initial adjustment and require continual programmer/operator attention as piece part batch variances are introduced into the process. The current requirement for human intervention introduces manufacturing delays and work flow stoppages, thereby reducing production efficiency. Many automation clients have sought the ability to reduce or eliminate the human factor involved in these requirements.

The challenge is to adapt the autonomous assembly system to the real-time dynamisms of data in a production system. This adaptation should be handled so that the essential performance criteria are maintained leading to economic profit and cost reduction purposes.

This work has investigated the impact of IoT on assembly system paradigms, when IoT can be applied in modern manufacturing enterprises. To achieve this objective, both the evolutions of IoT-based autonomous manufacturing paradigms are discussed. Also, a supervisory control and data acquisition (SCADA) system are adapted using IoT technologies for an autonomous assembly process. The autonomous system is equipped with robots for manufacturing task fulfillment. Then, due to dynamic data received from different operations and demands, assembly processes are configured and considering real-time fluctuations of data the assembly processes are reconfigured. The impact of IoT to control data dynamism and real-time data transfer through a modified SCADA system is substantial for optimality purposes. A mathematical model is formulated to handle the autonomous assembly process configuration/reconfiguration

The remainder of the paper is organized as follows. Next, the related works are reviewed. In Section 3, the manufacturing assembly system and autonomous assembly paradigms are introduced and an overview on principles of autonomy for both physical and control systems and introduces autonomous resources, products, and processes are presented. In Section 4, the IoT development model in a manufacturing assembly technology is discussed on autonomous processes on system level which includes the design of autonomous assembly systems, scheduling and control of assembly orders, and routing and transport of parts and subassemblies. In Section 5, the SCADA and IoT-based SCADA architecture are detailed. In Section 6, the proposed mathematical optimization in the designed SCADA system for configure–reconfigure decisions in an autonomous assembly system is reported. Section 7 conducts a numerical illustration followed by discussions and analysis in Section 8. Finally, the conclusions and future research directions are given in Section 9.

2. Related works

In this section, a brief survey of related works was provided. The survey does not span the entire field of configurable robotic systems. Instead, it focuses on systems for which autonomous assembly has been demonstrated.

Due to increasing market dynamics, planning, optimization, and control of assembly have become more challenging for manufacturing companies. Today, plans and schedules have to adapt quickly to a variety of products and changing market demands. But conventional structures and methods cannot handle changes, unpredictable events, and disturbances in a satisfactory manner. To manage these dynamics inside and outside an assembly system, a number of novel concepts for both the physical system and the control system were proposed and partly realized in the last decades. The most popular ones are FMSs and Reconfigurable Manufacturing Systems on the hardware side and the Holonic Manufacturing System and the Biological Manufacturing System on the software side. A configuration of autonomous flexible manufacturing system is shown in Fig. 1.

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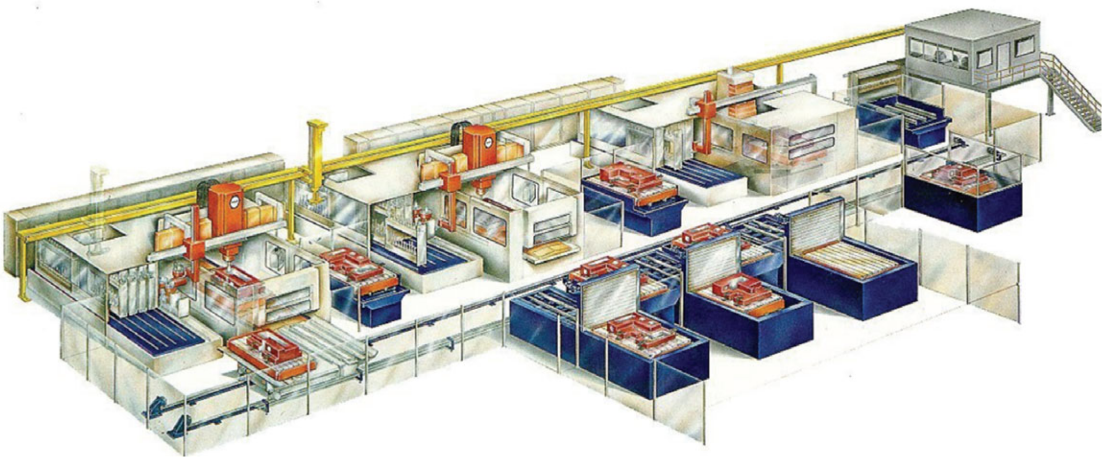

Figure 1. *An autonomous flexible manufacturing system (reference).*

The recent concepts have a common characteristic: the assembly system – consisting of a network of assembly stations or cells, buffers, transport systems, etc. – is clustered into subsystems and modules. These subsystems and modules get a certain degree of freedom to react on changes by themselves and adapt to new demands, and they are more or less autonomous. Autonomy in general means the independence of a system in making decisions by itself without external instructions and performing actions by itself without external forces. Approaches for (partly) autonomous systems are, e.g., autonomous production cells, automated guided vehicles, mobile autonomous robots, moving assembly stations, or dexterous robots with intelligent sensors.

IoT technologies are now been adopted to support a more effective management of safety in complex systems is currently a challenge for both researchers and companies [22]. Among the several IoT tools, radio-frequency identification (RFID) technologies could be an efficient tool: these technologies are widespread in industrial systems and services for the identification and traceability of products and/or people [16]. The RFID identification, unlike traditional barcode, uses radio waves to read the data encoded on electronic labels (or tags); the reading process – that occurs through an appropriate device – performance shall vary from a few centimeters to meters [23]. RFID technology allows identification of objects without contact, by using radio frequency transmission of information; the basic elements of an RFID system are the so-called tags (composed of an antenna and a chip) applied on or inside of the objects to be identified, and the reader, which communicates with the tags [3].

The application of autonomous subsystems is realized by recent information and communication technologies such asRFID, sensor technologies, and wireless communication networks. These ubiquitous computing technologies enable a high flexibility and changeability of assembly systems to manage today's increasing requirements. This paper mainly focuses on the intersection of the intelligent production control assemble system areas, and thus deals with IoT-based reconfigurable assembly systems and autonomous control concepts for assembly processes (see Fig. 2).

Manufacturing, through the Industry 4.0 concept, is moving to the next phase; that of digitalization. Industry 4.0 enables the transition of traditional manufacturing systems to modern digitalized ones, generating significant economic opportunities by reshaping of industry. This procedure requires high-performance processes and flexible production systems. The adoption of the IoT in manufacturing will enable effective and adaptive planning and control of production systems [15]. Smart manufacturing utilizes rich process data to enable accurate tracking and monitoring of individual products throughout the process chain. [9] developed the perception of, sensing in, and control of smart manufacturing systems by leveraging active sensor systems within smart products during the manufacturing phase. The

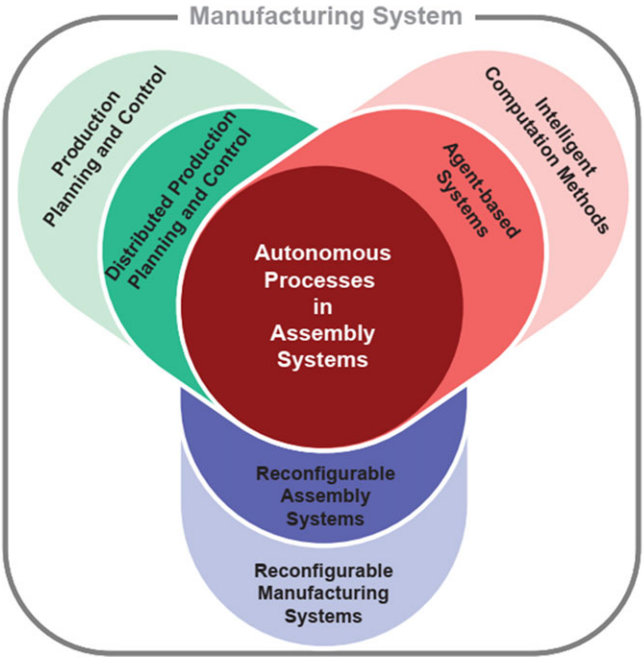

Figure 2. *Focus of the paper.*

continuous development of Internet communication technology has given birth to the development of IoT technology and the integration of intelligent manufacturing to accelerate the upgrading of traditional industrial production lines [6].

The IoT supports various industrial applications. The cooperation and coordination of smart things are a promising strategy for satisfying requirements that are beyond the capacity of a single smart thing. Since each IoT device includes one or more microservices, the increasing number of devices around the user makes them difficult to assemble in order to achieve a common goal. [8] proposed a self-assembling solution based on self-controlled service components taking into account nonfunctional requirements concerning the offered quality of services and the structuration of the resulting assembly. Human–robot collaboration is becoming a trend in manufacturing industry. However, the dramatic changes of requirements from the market put a higher demand for the flexibility of manufacturing systems. Cyber-physical production system that offers benefits of autonomy, self-organization, and interoperability can be adopted to increase the flexibility of manufacturing systems [24].

Autonomous, matrix-structured assembly systems are discussed as a promising approach for dealing with current challenges as high product variance. For production planning in such systems, the so-called volume cycle concept is proposed, in which a fixed-order volume per time unit is consolidated for assembly [17]. With rapid advances in new generation ITs, digital twin, and cyber-physical system, smart assembly has become a core focus for intelligent manufacturing in the fourth industrial evolution. Deep integration between information and physical worlds is a key phase to develop smart assembly process design that bridge the gap between product assembly design and manufacturing [25].

3. Reconfigurable autonomous assembly system

Autonomous robots are devices that are programmed to perform tasks with little to no human intervention or interaction. They can vary significantly in size, functionality, mobility, dexterity, intelligence, and cost – from robotic process automation to ?ying vehicles with artificial intelligence. Autonomous

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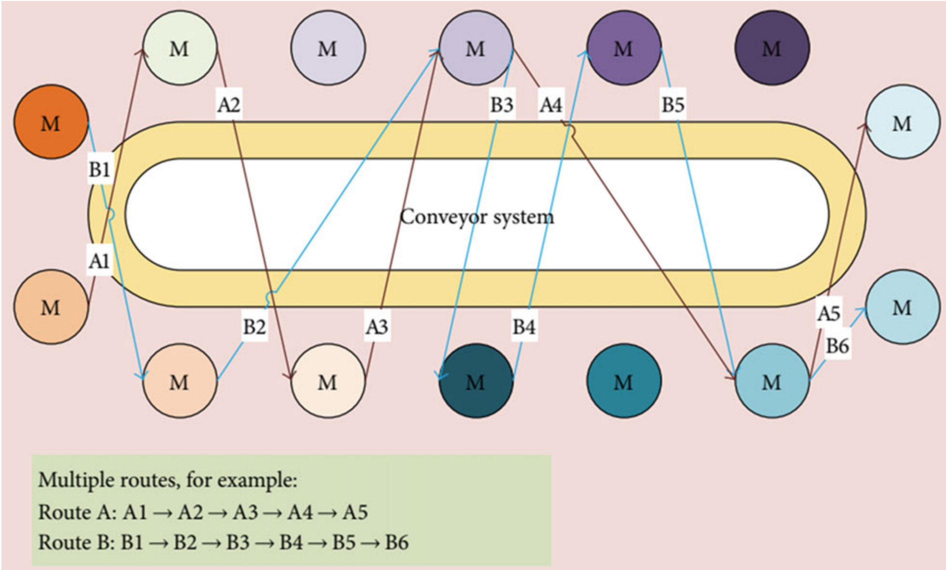

Figure 3. *A reconfigurable assembly system.*

robots can recognize and learn from their surroundings and make decisions independently. Autonomous robots are expected to see strong growth over the next period of time, particularly within supply chain operations that include lower value, potentially dangerous or high-risk tasks. Manufacturing, final assembly, and warehousing, for example, are areas where robots already have a presence; continued growth of autonomous robots could allow people currently performing these tasks to shift to more strategic, less dangerous, and higher value work.

Autonomy of a system implies two basic characteristics: First, independence from neighbor systems and from its environment, and second, the ability to control itself. The first characteristic can be reached by clustering an assembly shop into subsystems and modules with standardized interfaces. The second characteristic requires the decentralization of the control system according to the granularity of the subsystems and modules.

The need for clustering an assembly shop into subsystems and modules came up in the early 1990s when customized products and highly fluctuating demand could not be handled anymore by the former FMS. The quick changes in products, variants, and production volume required increased flexibility and adaptability of the assembly system. This led to reconfigurable manufacturing systems (RMS), which could be reconfigured regarding both capacity and functionality.

The reconfigurability was realized by building autonomous assembly cells that were connected by flexible transport systems such as automated guided vehicles. An assembly system consisting of flexibly connected autonomous cells can be adapted quickly to changing production volume and product mix. To increase flexibility and adaptability, the cells were built up of replaceable components and modules. A reconfigurable assembly system is illustrated in Fig. 3. It is illustrated that two separate assembly routes are using machines in common just by some adjustments and replacements increasing the flexibility to assemble multiple products through a manufacturing system.

Furthermore, autonomous robots were developed that are able to recognize their environment by sensors, to coordinate their work with other robots and assembly equipment, and to adapt the assembly process if new products had to be assembled. Such degree of autonomy requires also sensor-equipped grippers and manipulators that are able to act like a human hand. The research on such dexterous hands and fingers is still in progress.

To sum up, the following list shows examples for autonomous systems and resources, respectively, on the different system levels:

- System: e.g. shops as autonomous profit centers
- Subsystem: e.g. autonomous cells
- Machine: e.g. autonomous robots, AGV
- Component: e.g. dexterous grippers, artificial hands

These autonomous resources within an assembly system should be able to identify and locate themselves, to sense their environment, to communicate with other resources and with parts and subassemblies to be assembled or transported, and – last but not the least – to control themselves autonomously by using their integrated control system. These requirements are obvious for mobile autonomous robots and automated guided vehicles, but also needed for more conventional assembly equipment such as conveyors, stationary robots, and part feeders to realize autonomous assembly processes.

In the 1980s, the FMS were controlled by a central control system. Within the concept of CIM, all product and production data were integrated into a central database. Despite extensive research in CIM and the obvious advantages of this concept, some researchers already recognized the drawbacks of central control in hierarchical structures. Alternatively, heterarchical control architectures lead to reduced complexity by localizing information and control, to reduced software development costs by eliminating supervisory levels, higher maintainability and modifiability due to improved modularity and self-configurability, and improved reliability by taking a fault-tolerant approach rather than a fault-free approach. With the upcoming need for Reconfigurable Manufacturing Systems and the clustering of the assembly shop into subsystems and modules in the early 1990s, decentralized control approaches and heterarchical architectures came to the fore. Furthermore, the implementation of intelligent control strategies became required in order to adapt the system.

Recent research projects investigate the introduction of autonomous parts and subassemblies that are able to allocate transport and assembly resources by themselves and – in doing so – route themselves through the assembly system. A first step toward autonomous parts and subassemblies is the tagging or embedding of identification devices. There are, for example, first prototypical integrations of RFID devices into die casting metal parts. Such identifiable parts can be connected with the ERP system to get product data, process plans, and even data of customer orders. In a second step, some of these data can be directly kept on the part itself. For that, the simple RFID device has to be replaced by a chip with data storage, a processor, and a communication unit to exchange data between the part and the ERP system. The last step to a completely autonomous part is the integration of a software agent which is able to communicate with other parts and resources to coordinate all transport and assembly processes. The question whether the agent should be embedded into the physical part or could remain in a separate control system depends on the communication effort between different agents as well as the amount of data to be exchanged. A flexible solution is the use of mobile agents that are able to migrate from the control system to the physical object and vice versa.

4. IoT-based autonomous assembly operations control

Consider the scheduling of assembly and the routing of the parts through the assembly shop: Due to the high communication and coordination effort between parts and resources, the mobile agents would migrate into the control system. If the final products leave the assembly system, the agents could migrate back to the physical objects to autonomously control the distribution process of the products.

Mobile agents are a specific form of mobile code and the software agent's paradigm. They are active in that way they choose to migrate between computers at any time during their execution. This makes them a powerful tool for implementing autonomous parts and subassemblies in an assembly system. In general, a mobile agent is able to transport its state from one environment to another, with its data intact,

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and still being able to perform appropriately in the new environment. Mobile agents decide when and where to move next. A mobile agent accomplishes this move through data duplication. When a mobile agent decides to move, it saves its own state and transports this saved state to the next host and resume execution from the saved state. To sum up, the enabling technologies to realize autonomous products are as follows:

- Identification (e.g. RFID),
- Localization (e.g. RFID reader, WiFi, GPS),
- Communication (e.g. WiFi, UMTS),
- Decentralized data processing (e.g. software agents),
- Sensor networks (e.g. visual sensors).

The combination of autonomous resources on one hand and autonomous parts, subassemblies, and products on the other hand will lead to autonomous processes where parts and subassemblies allocate resources and coordinate their assembly by themselves. Such autonomous processes would lead to highly flexible and self-adaptable assembly systems which could make a variety of customized products and deal with fluctuating demand with only little or even no human interventions.

Scheduling of assembly systems is characterized by high complexity (number of orders, variety of products, and variety of resources). The general task of assembly scheduling is the assignment of operations to workstations, allocation of resources and building a schedule. The assembly scheduling problem is similar to the known job shop scheduling. But the assembly scheduling is even more complicated due to the fact that in an assembly sequence are often many candidate operations which can be performed next. In autonomous assembly systems, the schedule must be reactive to deal with uncertainty and disruptions. Disruptions should be treated at the system level where they appear. In general, the assembly scheduling problem is NP-complete and requires heuristic approaches to get feasible solutions in adequate time. In an assembly control system with reactive scheduling capabilities, the different components cannot be independently programmed since an assembly system is a distributed system and the different workstation programs will run in parallel, exchanging information for synchronization and coordination purposes. One approach is a completely heterarchical control system where intelligent products and parts drive their own production in cooperation with intelligent manufacturing resources. By locating decision-making where information originates, global information is claimed to be reduced to a minimum, scheduling becomes dynamic, machines and parts become intelligent entities that cooperatively interact, and the overall system is decomposed into functionally simplified, modular parts. The key advantage of heterarchical manufacturing control is the much reduced exposure of the software components in the system. Global information is reduced to a minimum in the system. Parts to be manufactured are programmed as intelligent entities that cooperatively interact with intelligent robots and processing machines. Human entities have also been included that cooperate as colleagues of the other entities in the system. This system design resulted in reduced complexity, higher fault tolerance, shorter development times, and lower development costs.

The material flow through an assembly system can be classified into the transport of (partly assembled) products from station to station or from cell to cell and the transport of parts and tools to the stations or cells. Material flows in assembly systems also include the internal transport within cells and the part feeding. The moving vehicles are completely passive and are controlled by the cooperating propulsion units. The applied routing algorithm does not require a global map of the transportation network. The guideway network and the communication network are unified to combine system level and vehicle control to realize on one hand high vehicle speeds and short response times and on the other hand a self-configuring, extensible, fully distributed control. This system architecture was used for material transfer within an experimental manufacturing system to deliver tools to and from machines.

The AGVs transport parts and subassemblies between assembly stations and cells whereby they autonomously decide about their particular routes. The AGVs have laser scanners to determine their position on the shop floor and infrared sensors to recognize obstacles. Each AGV has a control system by its own which realizes not only the routing and control of the AGV but also all decision-making and coordination tasks for the processing of transport orders and collision avoidance. Agents are used to schedule transport orders in that way that all AGVs are evenly utilized. For this, agents negotiate between AGVs and stations in real time. The algorithms for decision-making are kept in agents that accompany the parts and subassemblies by migrating from one station to another. This system of autonomous AGVs with agent based, distributed control achieves a high and constant utilization of the AGVs even in a highly dynamic environment and can autonomously compensate breakdowns of single AGVs.

5. Modified SCADA automation system

SCADA is a system of software and hardware elements that allows industrial organizations to:

- Control industrial processes locally or at remote locations
- Monitor, gather, and process real-time data
- Directly interact with devices such as sensors, valves, pumps, motors, and more through human-machine interface (HMI) software
- Record events into a log file

SCADA systems are crucial for industrial organizations since they help to maintain efficiency, process data for smarter decisions, and communicate system issues to help mitigate downtime. The SCADA software processes, distributes, and displays the data, helping operators and other employees analyze the data and make important decisions. The basic SCADA architecture, as shown in Fig. 4, begins with programmable logic controllers (PLCs) or remote terminal units (RTUs). PLCs and RTUs are microcomputers that communicate with an array of objects such as factory machines, HMIs, sensors, and end devices and then route the information from those objects to computers with SCADA software.

SCADA systems are used by industrial enterprises to control and maintain efficiency, distribute data for smarter decisions, and communicate system issues to help mitigate downtime. SCADA systems work well in many different types of enterprises because they can range from simple configurations to large, complex installations. The SCADA system required for advanced and complex manufacturing systems employed today needs to adopt networking systems. In the modified system, the communication between the system and the master station is done through the WAN protocols like the Internet Protocols (IP). Since the standard protocols used and the networked SCADA systems can be accessed through the internet, the vulnerability of the system is increased. However, the usage of security techniques and standard protocols means that security improvements can be applied in SCADA systems (Fig. 5).

6. Mathematical optimization

Originally, the conveyor assembly line is built with multiple workstations and workers with differentiable operating abilities. Various product types are processed on the conveyor assembly line under a given dispatching rule, e.g., EDD (Earliest Due Date), FCFS (First Come First Serve), SPT (Shortest Processing Time), etc. Blocking and starving cases are not rare on the conveyor assembly line because of the capacity variance of workers on line. The performance of the traditional manufacturing system is also bound up with the bottleneck process. The bottleneck process increases the make span and yields a low motivation among the skillful workers. Furthermore, the frequent shiftings between two different product types result in hard-win and time-consuming setup activities and a waste of production time and capacity. Consequently, the conveyor assembly line is reconfigured to mitigate or overcome the drawbacks of the traditional manufacturing system.

A few knowledge-based approaches for automated design of production systems have been reported in literature. While the support tools described by Khan et al. (2011) generated single system design solutions for their respective design problems, only two approaches have been found that generate and present multiple system configurations for a given production problem and allow the users to compare

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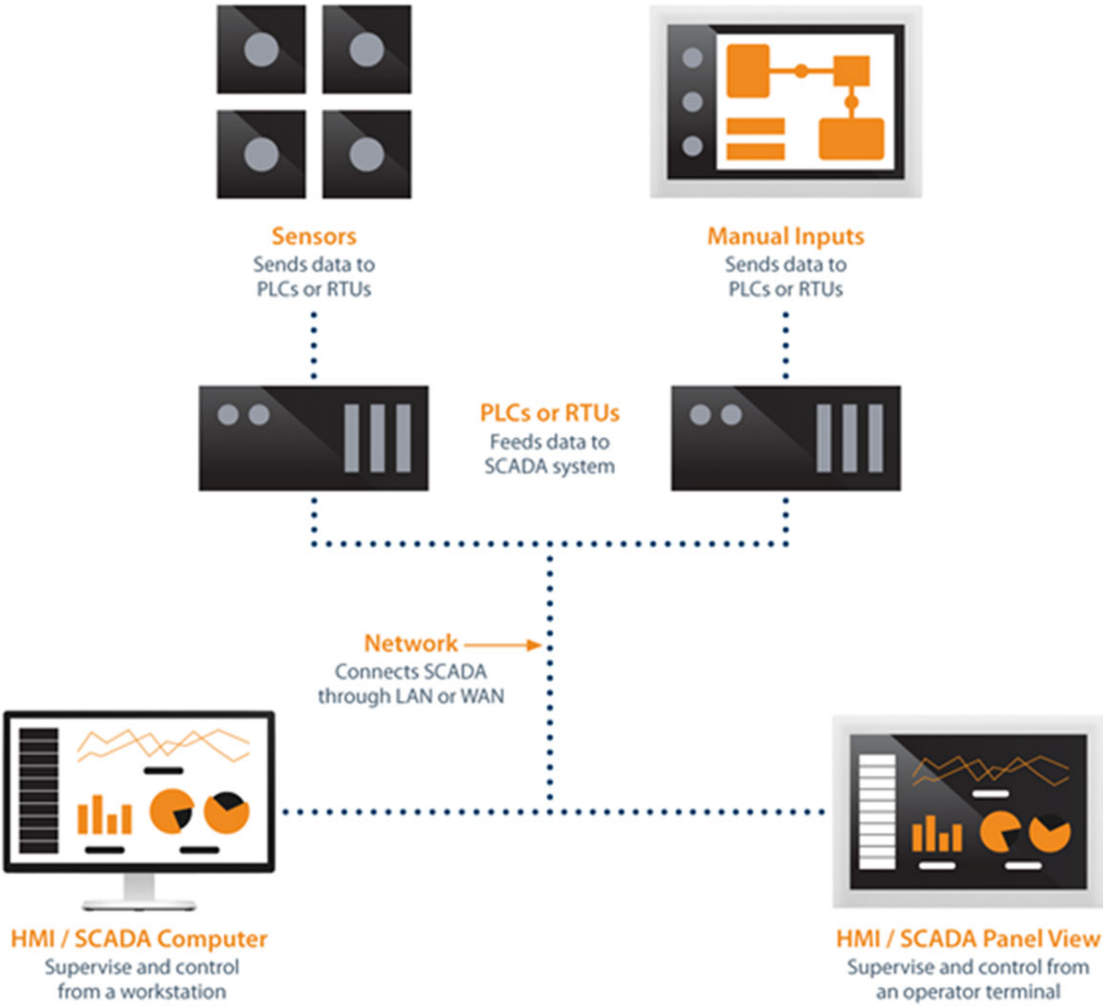

Figure 4. *A basic SCADA diagram.*

the alternatives. In these approaches, however, the comparison focuses on the performance properties of the systems [13] or aims at configuring an individual dedicated transfer line [2]. Many opportunities exist for allocating the production resources J and products P to multiple production cells and make possible a vast number of production system configurations with differing performance profiles. Hence, the Assembly System Configuration aims to explore a large variety of solutions, which can consist of one or more cells and fulfill design and performance requirements simultaneously.

Therefore, the Assembly System Configuration system automatically generates many configurations of the assembly system and analyzes their key performance indicators (KPIs) to enable the exploration of the design space. To achieve this objective, multiple steps of design synthesis and analysis are executed in an automated way for each candidate solution. At the beginning, the system determines the number of assembly cells in the system, afterward the production equipment is selected and assigned to the cells; as the last design step, the products are assigned to cells. Once the design is completely specified, the KPIs of the synthesized solution can be determined. All candidate configurations are examined so that the decision-makers can explore the design properties and performances of the solutions. Based on these characteristics, the users can specify feasible regions of the design space by imposing constraints

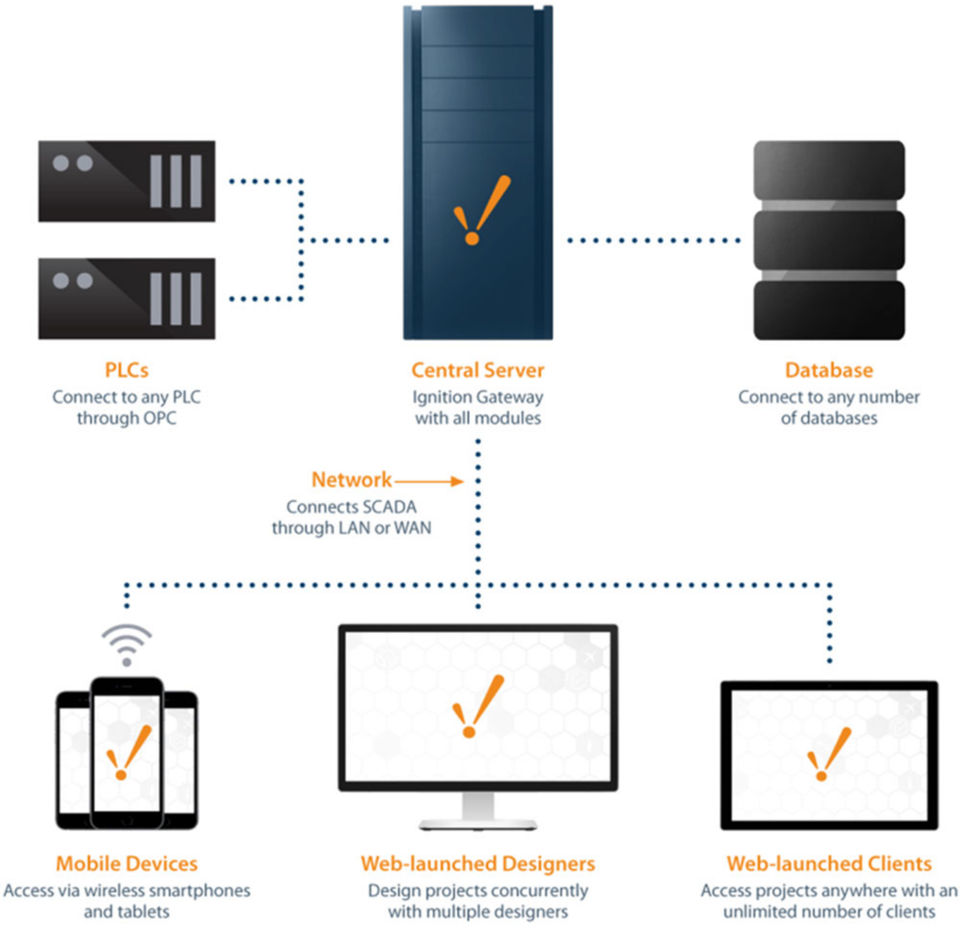

Figure 5. *IoT-based SCADA.*

and generating new solutions, or selecting the most suitable system configurations. By iteratively specifying design or performance constraints, generating matching solutions, and assessing the results, the knowledge-based enables to concurrently assess various options to configure the production system, and facilitates developing feasible assembly system configurations.

Due to the evolution of the market requirements, in terms of product types to produce and their volumes, and the upgrading of the available assembly technologies in time, an assembly line design can easily become inappropriate and can require reconfiguration over time. Therefore, the assembly line design and management method must be able to cope with the evolution of requirements, also addressing how and when the assembly line configuration must change to match the new production needs. To model the uncertain evolution of requirements, a probabilistic scenario model is proposed. A set of nodes O is defined, over a set T of periods. For each node, a probability of realization $P(O)$ is assigned at the beginning of the considered period (t_0). Each scenario node is characterized by a set of production requirements to be guaranteed if the realization of that specific scenario occurs, leading to a tree structure modeling the evolution of the requirements over the time horizon (t_0, t_1, t_2, . . ., T). The root node represents the current production problem to be addressed and is assumed to be perfectly known (see Table I).

In detail, the set of products Po to be produced is associated to a scenario o. A volume $d_{p(o)}$ of products in Po must be delivered to the customers, under the hypothesis of an average lot size $lp(o)$. For

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Table I. *Summarized information flow in the assembly system configuration.*

Input from database	**Product information (P, T, O)**
Input before runtime	Resource information (J)
Solution approach	Scaling factors (SF_c, SF_{op}) Requirements for design and performances (R) (I) User enters scaling factors SF_c , SF_{op} and R (II) Algorithm creates and analyzes configurations (III) Preliminary configurations S_{prel} (IV) User assesses configurations Optional : user refines by iterating (I)–(IV) (V) User selects preferred configurations S
Main output	Feasible, preferred system configurations S

each product p in P, the assembly process requirements are expressed in terms of Functional Assembly Groups (FAGs). FAGs include modular hardware components required for a class of assembly operations, e.g., resistance spot welding, glueing, hemming, self-pierce riveting, laser brazing, remote laser welding, etc. A FAG consists of one or more pieces of equipment, together with the needed tools and fixtures, to carry out the operation. However, resources, such as handling and transportation devices (e.g., robots), can be shared between different FAGs. The FAGs required to assemble a part type P are contained in the set *Jp(o)*, and the associated technological requirements, e.g., the number of joints, the hemming length, etc., are contained in the set *DELTAj,p(o)*. Unitary processing times required for each FAG (the time per spot or the time per mechanical joint) are provided in the set *Mj,p(o)*. Furthermore, *Sp(o)* provides the assembly sequence for each part type, typically requiring multiple FAGs. Additional nonoperational data regarding each FAG, dealing with the floor space requirements, investment costs, and depreciation years, are also taken into account.

The design problem consists in the selection of the FAGs, the classes of equipment within them, and their organization into different assembly cells. Moreover, for each cell, the specific layout, the parts to be produced, and the task sequences to be executed are defined. These decisions must be taken with the objective to minimize the expected configuration–reconfiguration costs, over the whole set of scenario branches. Every time a move to a new node happens, a major reconfiguration step can be implemented, to evolve to a new configuration matching the changed production requirements. The aim of the approach is to drive the coevolution of the assembly line, the product, and the process, based on the requirements over the whole set of scenarios, to provide a robust assembly line design solution. In this design problem, robustness refers to the capability of guaranteeing the requested level of performance irrespective of internal and/or external disturbances. This can be achieved acting proactively, i.e., paying for a suboptimal configuration (paying for redundancy or overcapacity) to be ready to manage future changes without the need of reconfiguring or reactively acquiring the capability to rapidly react to the changes in the right way (in the considered problem this is enabled by modularity).

Based on the detailed cell designs and the production parameters provided by the layout configuration module, the production planning and control module are responsible for testing the robustness of the designed system under specific due dates imposed by the customers. The first production planning activity optimizes the production schedule and the lot sizes for user-defined due-time performance. Besides, a control tool evaluates the defined system configuration under the specific schedule, considering the effects of stochastic parameters and random events on logistics-related performance indicators. The input of the production planning activity is the set of products that are assembled in the system, the number of available resources, the detailed layout of the system, as well as the due dates coming from the customers. Due dates can be predicted in the early system configuration stage by knowing contractual

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delivery frequency requested by the customer, and they have significant impact on the applied production lot sizes and, therefore, the operational costs. The control tool is directly linked to the production planning activity, as the main inputs of the analysis are the calculated production plan, the system configuration with detailed data of the processes, as well as logistics-related data, e.g., actual inventory and backlog levels. Production planning is done on a discrete time horizon W, and the resolution of the plan is a working shift (w). The objective is to calculate the production lots $x_{p,w,c}$ with respect to the available capacities, cycle (${t^m}_p$) and setup (t^s) time constraints. In the model, set-ups are expressed with the binary variables $z_{p,w,c}$ and $y_{p,w,c}$. When assembling a certain product type, a definite amount of FAGs $r_{j,p}$ is required, and a given amount n_j of FAGs from each type j is available for use at the beginning of the period. The order demands dp need to be satisfied by delivering certain amount $s_{p,w}$ of products to customers. In the production planning, holding inventory of products ($i_{p,w}$) is allowed; however, it has certain costs c^i. Similarly, planned backlogs ($b_{p,w}$) might occur, but they are also penalized with cost c^b per product and shift. The objective (1) of the problem is to minimize the total backlog and inventory costs that incur in the period. Production planning is formulated as an integer programming problem:

$$\min \sum_p \sum_w \left(c^b b_{p,w} + c^i i_{p,w} \right). \tag{1}$$

s.t.

$$\sum_c \sum_p r_{j,p} y_{p,w,c} \leq n_j, \qquad \forall w, j, \tag{2}$$

$$\sum_p \left(t_p^m x_{p,w,c} + t^s z_{p,w,c} \right) \leq t^p, \qquad \forall w, c, \tag{3}$$

$$d_p \leq s_{p,w}, \qquad \forall p, w, \tag{4}$$

$$i_{p,w} - b_{p,w} = i_{p,w-1,c} - s_{p,w} + \sum_c x_{p,w,c}, \qquad \forall w, p. \tag{5}$$

The first constraints include the limited amount of FAGs (2) and human capacities (3). Inequality (4) states that demands must be fulfilled, and the balance Eq. (5) links the subsequent production shifts. For the calculation of the setups ($z_{p,w,c}$ and $y_{p,w,c}$), the multi-item single-level lot sizing model was applied (LS-C-B/M1). The cell-product assignments ($a_{p,c}$, equals 1 if product p is assigned to cell c, 0 otherwise) are determined by the previous modules; however, the assignment of resources to cells needs to be optimized by the production planning module, to avoid conflicts.

6.1. *Reconfiguration planning module:*

A different perspective must be adopted when addressing a longer time horizon. The set of products P to be produced can vary over time and also the assembly cells in the system could need to be suitably reconfigured. It could be necessary to dismiss pieces of equipment or insert new ones or move them among assembly cells. These decisions must ground on the evolution of the production requirements modeled. As these requirements change, moving along nodes in the tree, the design of the cells can change as well, thus undergoing reconfiguration. In the reconfiguration planning module, all the possible evolutions of an assembly line's configuration are considered. Each of them refers to a specific path from the root of the scenario tree to a leaf and is associated to an occurrence probability. Nevertheless, different paths in the tree share a subset of nodes and, in this subset, they must also share the same configuration. Given this set of constraints, it is possible to formulate an optimization problem, looking for the best reconfiguration steps for the different scenarios, with the aim at achieving robustness over the whole scenario tree. In some cases, it will be advisable to acquire resources in advance or, if the occurrence probability is low, to wait until a specific scenario occurs and, hence, acquire the needed pieces of equipment.

Figure 6. *Proposed IoT-based autonomous assembly system.*

The reconfiguration strategy aims at minimizing an objective function (6) considering the expected value of the incurred cost over all the scenarios:

$$\min \left(IC_0(e) + OC_0(e) + \sum_{o} P_o \frac{IC_o(f\,|e\,) + OC_o(f\,|e\,)}{(1 + q^{stage\ \ o}}\right). \qquad (6)$$

where *ICo* and *OCo* are the investment and operation cost in scenario node *o* (*Os* is the set of scenario nodes) and depend on the initial configuration decisions (*e*) and the reconfiguration actions (*f*); for the root node (node 0), they only depend on *e*. The discount rate is *q*, and stage *o* is the time stage of the considered scenario node. Only the configurations respecting the production requirements and generated at different levels of detail by the modules are considered for the optimization.

The output of the proposed approach is an initial configuration for the assembly lines, together with appropriate reconfiguration steps associated to the different nodes in the scenario tree.

7. Implementation of a proposed IoT-based autonomous assembly system

Using radio technologies, it is also possible to employ new, mobile, and flexible systems for the operation, maintenance, and diagnostics of the production facility. Today, most sensors and actuators as well as more complex mechatronic units are equipped with stationary, inflexible control panels that range from those with just a few buttons and lights to those with complete PC-based, color LCD panels. Due to the lack of standards and the increasing range of functionalities, the complexity of these device operating systems is rapidly growing, a fact which not only leads to higher costs but also to problems in familiarization training and maintenance service. One solution to this problem is the physical separation of the devices and the control panels. Radio technologies enable standard control devices such as PDA's or mobile telephones to access different suppliers' field devices. A widely standard, consistent control concept raises the learning conduciveness of such systems and prevents operational errors. Location independence and the advanced display and interactive possibilities enable a significant increase in the flexibility of device operations (Fig. 6). The integration of location sensing systems with production and logistic processes is a major condition for meeting the demands for greater flexibility and shorter production cycles. The effective use of location data allows for flexible context-related applications and location-based services. Various positioning systems are deployed. For example, the floor is fitted with a grid of RFID tags. These tags can be read by mobile units to determine location data. Other systems for three-dimensional positioning based on ultrasonic as well as RF technologies are also installed.

Scan data of real factory equipment, in point cloud form, are integrated with virtual data in the simulation environment for more accurate and timely analysis. In this past, this task took weeks, with many engineers needed to scan and measure the production facility. By eliminating that step, the new technology will permit faster modifications, a critical requirement for autonomous production. Similarly, event-driven simulation (also known as discrete event simulation), which is already available, will play a bigger role as a fundamental tool for enabling autonomous production. This is because behind the flexibility and autonomy of this type of production scenario, there are very rigid rules that the system must adhere to. The self-driving vehicle is a good example – without strict rules, these cars would wreak havoc. The challenge is to move from nominal planning to variable planning, where the result is driven by the varying surrounding conditions in the ecosystem. We already know that manufacturing is a key driver for economic growth, attracting investments, spurring innovation, and creating high-value jobs. All of the breakthrough and developments that are happening now – the building blocks for autonomous production – are already adding economic value. Imagine what will happen when autonomous production is routine. Not only is it likely to be the revival that many predict for the manufacturing industry. We also see autonomous production as a way to address many global challenges such as a growing and aging population, climate change, and resource scarcity.

The practical relevance of the framework was proven in an industrial case study provided by a medical device company located in the northern part of Iran; first device supplier of a medical body managed in built to order mode. Due to the increasing number of device variants offered by original equipment manufacturers, a fragmentation of the absolute demand volume makes necessary a change in production particularly for spare parts, whose declining volumes make economic production an increasingly challenging endeavor. Consequently, the frequent design, implementation, and reconfiguration of the assembly line are a suitable concept to proactively manage the variable product volumes. To support these tasks, a scenario tree is considered, describing multiple, anticipated developments of production requirements (Table II). The scenario nodes are named according to the time period they refer to, hence o_0 is the root node while $o_{1A}(o_0)$ is a node related to time period 1 whose ancestor node is o_0. For each node, the production volumes for the different products are considered (products are not explicitly reported for confidentiality reasons). Also the FAGs requirements for each product are reported. For each class of operations, we refer to needed tools and process times, e.g., product 1 requires the Mechanical Join FAG using tool *T1* for 10 s; product 3 also requires that FAG using tool *T1* for 25 s and *T2* for 8 s (Table II, last three rows).

Based on this input information, the proposed approach has been applied for each of the considered scenario nodes. First, the design synthesis module generates design candidates according to different production strategies and analyses their performances. To cope with the large solution state space, design and performance constraints can be imposed: performance, investment cost, and maximum number of FAGs implemented in a cell have been used for this application case.

The results of the whole approach applied on scenario path o_0 -o_{1A} -o_{2B} are reported in Table III. First row refers to the robust solution, obtained by applying Eq. (6). Second row refers to the optimal solution for the considered scenario path only, obtained by choosing the best configuration solution at each step (reconfiguration costs foreseen). Last row reports the solution in which optimal solution for o_0 is used in every time bucket. The solutions are compared in terms of purchasing, reconfiguration, storage, and operational costs. Results demonstrate that the robust solution ensures a lower total discounted cost compared to the optimal solution for the single scenario path (771,730 $ against 806,909 $), the difference is mainly due to the fact that the robust solution behave proactively, purchasing additional pieces

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Table II. *Product demand scenarios and process information for input.*

Scenario nodes	Products Prod. 1	Prod. 2	Prod. 3	Prod. 4
o_0	7500	0	9000	0
$o_{1A}(v_0)$	0	0	8500	7500
$o_{1B}(v_0)$	0	0	7500	5000
$o_{2A}(v_{1A})$	5200	8300	4800	2300
$o_{2B}(v_{1A})$	5000	8000	4500	2000
$o_{2C}(v_{1B})$	4500	700	4500	2000
$o_{2D}(v_{1B})$	4000	6500	4000	2000
$o_{2E}(v_{1B})$	3500	600	4000	2000
FAGs				
OP1: Mechanical join (Tool-ID, duration)	T1, 10 s	–	T1, 25 s T1, 18 s	T2, 8 s
OP2: Resistance join (Tool-ID, duration)	T1, 192 s	T1, 102 s	T2, 177 s	T2, 198 s
OP3: Adhesive join (Tool-ID, duration)	T2, 25 s	T1, 27 s T2, 13 s	-	-

Table III. *Numerical results for the industrial real case.*

	Cost type	t_1	t_2	t_3	Total
Robust approach (overall approach)	FAG purch	358,883	0	0	358,883
	Module purch	50,000	0	0	50,000
	Reconfiguration	0	0	0	–
	Storage	0	12,000	0	12.000
	Operative	92,010	106,002	78,894	276,906
	Tool purch	45,000	20,000	20,000	85,000
	Total (discount)	545,893	133,412	92,425	771,730
Single path optimum (best configuration is chosen for each scenario)	FAG purch	358,883	0	0	358,883
	Module purch	40,000	0	10,000	50,000
	Reconfiguration	0	10,000	10,000	20,000
	Storage	0	18,000	0	18,000
	Operative	100,776	103,542	83,850	288,168
	Tool purch	45,000	20,000	20,000	85,000
	Total (discount)	544,659	146,502	115,748	806,909
Single node optimum (best o_0 configuration is used in every scenario)	FAG purch	358,883	0	Infeasible solution	358,883
	Module purch	40,000	0	Infeasible solution	40,000
	Reconfiguration	0	10,000	Infeasible solution	10,000
	Storage	0	18,000	Infeasible solution	18,000
	Operative	100,776	103,542	Infeasible solution	204,318
	Tool purch	45,000	20,000	Infeasible solution	65,000
	Total (discount)	544,659	146,502	-	691,161

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of equipment in advance, while the other solution has to react to the changes through a reconfiguration step, whose impact on the cost is relevant (10,000 $).

8. Discussions

Even with the growing proliferation of the IIoT, we are not at the point where autonomous production is widespread or routine, although there are some plants implementing some elements of it today. What is already widespread and routine, however, is the solid foundation for autonomous production, which can be seen in practice in the many plants that have adopted digital manufacturing. Digital manufacturing solutions provide manufacturers with vast capabilities for designing and evaluating their processes virtually. In a digital manufacturing environment such as our company's manufacturing planning and management solutions, the physical world is replicated in a model-driven database. Digital tools and methods are used to design the physical manufacturing system, including its logical controls. The result is a comprehensive virtual model of the manufacturing process that crosses multiple engineering disciplines such as tooling, process, logistics, quality, and product. Digital simulation tools make it possible to validate and optimize the processes, tools, and the control algorithms, and the interactions between them, all in a virtual environment prior to commissioning the system on the shop floor. Beyond digital manufacturing is the digital factory, which is composed of additional technological layers. A digital factory requires an infrastructure to connect the devices, the ability to identify where connectivity legitimately adds value and is not merely intrusive, and software platforms that will unlock the torrent of data.

To put the Digital Factory in its proper place on the road to autonomous production, we need to look first at how it can improve manufacturing flexibility, since that is a critical element of autonomous production. Traditional production uses a sequential process flow between production modules (a moving line), where each module has a dedicated task to perform in a given sequence.

A flexible process flow between production modules, made possible by Digital Factory solutions, allows different modules to be configured for each production instance. Such a production system is more resilient to changes and allows greater variation in manufacturing scenarios (production mix, production volume) and product range. Digital Factory solutions optimize production asset utilization by constantly monitoring, controlling, and analyzing the production ecosystem and making online decisions. They can do this for physical assets, such as machines, inventory, or energy consumption, such as time to completion. Additional technologies are still needed before autonomous production is a reality, but they are arriving on a regular basis. For example, Siemens PLM Software and our partner, Bentley Systems, recently introduced a new point cloud technology that makes it possible to capture the exact position of the production and logistical assets on a shop floor, providing in almost real time the actual conditions of the shop floor.

For analytical comparison purpose, the proposed SCADA system is compared with the traditional one. The required settings are performed to the system and the mathematical model is implemented. It should be noted that due to lack of internet communications among the components of traditional SCADA system, the smart and real-time data transfer and decisions are not possible. Therefore, the reconfiguration phase is completely useless. Therefore, the second objective function is not included. The objective function value of the configuration phase using traditional SCADA is obtained to be 987,320 $, which is more than the case the proposed SCADA is applied considering that the reconfiguration phase is not included. The reason is that by smart data interchange between components of the proposed SCADA, the optimization effort is decreased and the large amounts of cost elements are not incurred to the system. While in the traditional SCADA, the model should compare different configuration scenarios by several cost elements and as a result the total cost increases.

9. Conclusions

The IoT needs both data collection and actuation features, but it also needs contextual information and orchestration to make this data useful and enable automation scenarios to be built around it. Although IoT can be integrated into shop floor systems relatively easily, having an MES that supports the necessary decentralized logic of the smart shop floor will enable automated production of customized products. With the emerging ITs, such as IoT, big data, and cloud computing together with artificial intelligence technologies, it is believed that the smart factory of Industry 4.0 can be implemented. The smart machines and products can communicate and negotiate with each other to reconfigure themselves for flexible production of multiple types of products. The massive data can be collected from smart artifacts and transferred to the cloud. This enables the system-wide feedback and coordination based on big data analytics to optimize system performance. The above self-organized reconfiguration and big data-based feedback and coordination define the framework and operational mechanism of the smart factory. The smart factory helps to implement the sustainable production mode to cope with the global challenges. It can lead to novel business modes and even affect our lifestyle. Although the implementation of smart factory is still facing some technical challenges, we are walking on the right path by simultaneously applying the existing technologies and promoting technical advancements. With the existing technologies, some application demonstrations have already been built. Therefore, the smart factory and the Industry 4.0 can be implemented in a progressive way, along with the unstopped technical advancements. In the future, we will continue to develop our prototype design and focus on the key enabling technologies. The technologies that are purposed are those related to business intelligence module integrated in enterprise resource planning software application. This way, other significant modules related to production systems in industry 4.0 era, specifically, maintenance 4.0 could be included in the comprehensive decision making. Maintenance 4.0 is very effective in reconfiguration phase of the proposed model since it is a cost-related factor.

References

[1] S. Burnwal and S. Deb, "Scheduling optimization of flexible manufacturing system using cuckoo search-based approach," *Int. J. Adv. Manuf. Technol.* 64(5–8), 951–959 (2013).

[2] X. Delorme, A. Dolgui and M. Y. Kovalyov, "Combinatorial design of a minimum cost transfer line," *Omega* **40**(1), 31–41 (2012).

[3] V. Elia, M. G. Gnoni and A. Lanzilotto, "Evaluating the application of augmented reality devices in manufacturing from a process point of view: An AHP based model," *Exp. Syst. Appl.* **63**, 187–197 (2016).

[4] R. Erol, C. Sahin, A. Baykasoglu and V. Kaplanoglu, "A multi-agent based approach to dynamic scheduling of machines and automated guided vehicles in manufacturing systems," *Appl. Soft Comput.* **12**(6), 1720–1732 (2021).

[5] M. Gen and L. Lin, "Multiobjective evolutionary algorithm for manufacturing scheduling problems: state-of-the-art survey," *J. Intell. Manuf.* **25**(5), 849–866 (2014).

[6] X. Huang, "Intelligent remote monitoring and manufacturing system of production line based on industrial Internet of Things," *Comput. Commun.* **150**, 421–428 (2020).

[7] S. Latif, Z. Idrees, J. Ahmad, L. Zheng and Z. Zou, "A blockchain-based architecture for secure and trustworthy operations in the industrial Internet of Things," *J. Ind. Inf. Integr.* **21**, 100190 (2021).

[8] F. Lemoine, T. Aubonnet and N. Simoni, "Self-assemble-featured Internet of Things," *Future Gener. Comput. Syst.* **112**, 41–57 (2020).

[9] J. Lenz, E. MacDonald, R. Harik and T. Wuest, "Optimizing smart manufacturing systems by extending the smart products paradigm to the beginning of life," *J. Manuf. Syst.* **57**, 274–286 (2020).

[10] Q. Li, Z. Y. Wang, W. H. Li, J. Li, C. Wang and R. Y. Du, "Applications integration in a hybrid cloud computing environment: modelling and platform," *Enterp. Inf. Syst.* **7**(3), 237–271 (2013).

[11] K. Mao, G. Srivastava, R. M. Parizi and M. S. Khan, "Multi-source fusion for weak target images in the Industrial Internet of Things," *Comput. Commun.* **173**, 150–159 (2021).

[12] V. Marik, R. W. Brennan and M. Pechoucek, (eds.) Holonic and Multi-Agent Systems for Manufacturing (Springer, Berlin, Germany, 2005).

[13] G. Michalos, S. Makris and D. Mourtzis, "An intelligent search algorithm-based method to derive assembly line design alternatives," *Int. J. Comput. Integr. Manuf.* **25**(3), 211–29 (2012).

[14] L. Monostori, J. Váncza and S. R. T. Kumara, "Agent-based systems for manufacturing," *Ann. CIRP* **55**(2), 697–720 (2006).

[15] D. Mourtzis and E. Vlachou, "A cloud-based cyber-physical system for adaptive shop-floor scheduling and condition-based maintenance," *J. Manuf. Syst.* **47**, 179–198 (2018).
[16] D. Mourtzis, E. Vlachou and N. Milas, "Industrial big data as a result of IoT adoption in manufacturing," *Procedia CIRP* **55**, 290–295 (2016).
[17] D. Mueller and T. V. Schmitt, "Production planning in autonomous and matrix-structured assembly systems: effects of similarity of precedence graphs on order release sequencing," *Procedia CIRP 93*, 1358–1363 (2020).
[18] E. W. T. Ngai, D. C. K. Chau, J. K. L. Poon, A. Y. M. Chan, B. C. M. Chan and W. W. S. Wu, "Implementing an RFID-based manufacturing process management system: lessons learned and success factors," *J. Eng. Technol. Manage.* **29**(1), 112–130 (2012).
[19] A. N. Njike, R. Pellerin and J. P. Kenne, "Simultaneous control of maintenance and production rates of a manufacturing system with defective products," *J. Intell. Manuf.* **23**(2), 323–332 (2012).
[20] F. Ounnar and P. Pujo, "Pull control for job shop: Holonic manufacturing system approach using multicriteria decision-making," *J. Intell. Manuf.* **23**(1), 141–153 (2012).
[21] D. G. S. Pivoto, L. F. F. de Almeida, R. da Rosa Righi, J. J. P. C. Rodrigues, A. Baratella Lugli and A. M. Alberti, "Cyber-physical systems architectures for industrial internet of things applications in Industry 4.0: a literature review," *J. Manuf. Syst.* **58**(Part A), 176–192 (2021).
[22] A. Rymaszewska, P. Helo and A. Gunasekaran, "IoT powered servitization of manufacturing – an exploratory case study," *Int. J. Prod. Econ.* **192**, 92–105 (2017).
[23] K. Thramboulidis and F. Christoulakis, "UML4IoT—A UML-based approach to exploit IoT in cyber-physical manufacturing systems," *Comput Ind.* **82**, 259–272 (2016).
[24] B. Yao, Z. Zhou, L. Wang, W. Xu, J. Yan and Q. Liu, "A function block based cyber-physical production system for physical human–robot interaction," *J. Manuf. Syst.* **48**(Part B), 12–23 (2018).
[25] Y. Yi, Y. Yan, X. Liu, Z. Ni, J. Feng and J. Liu, "Digital twin-based smart assembly process design and application framework for complex products and its case study," *J. Manuf. Syst.* **58**(Part B), 94–107 (2021).

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