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Smart Adaptable Assembly Systems

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Abstract

In today's manufacturing environment, change has become a constant. Modern assembly systems must adapt to products, markets, technologies and regulatory requirements. The assembly industry is undergoing vast changes with the rapid development of production automation, process control, information technologies and networking. Variant-oriented assembly systems have been developed to achieve more flexibility and adaptability to enable adding product variants and scaling production. Smart assembly systems where intelligence is embedded in the products, work stations and system are emerging to achieve more autonomy in communication between entities in the system and more adaptable control of assembly flow and system performance. This paper highlights some advances in assembly technologies and systems and new trends of modularity and reconfigurable using a modular and reconfigurable assembly system. Future directions and challenges are outlined.

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Keywords: assembly; advances; technologies; products; processes; systems; changeability

1. Introduction

Assembly is a very important process in manufacturing. Assembly of manufactured goods accounts for over 50% of total production time and 20% of total production cost. In the automotive industry, 20% - 70% of the direct labour costs are spent on assembly. These statistics indicate the relative importance of assembly and point to the potential savings to be achieved by improving assembly technology and systems. Assembly is more than placing parts together. It is the capstone process in manufacturing and brings together all the upstream processes of design, engineering, manufacturing, and logistics to create a functional product [1, 2]. A major concern in manufacturing is the management of increased product varieties [3, 4, 5]. Large companies are gradually embracing and applying the concept of flexible manufacturing introduced more than 2 decades ago. Small and medium size companies are slower to adopt and implement automation and advanced manufacturing technologies in their operations. The wide scope of products variants driven by customers' preferences and dynamic fluctuation in the number of variants to be produced annually introduce manufacturing challenges which directly impact the manufacturing systems design and operation to cope with products and markets changes efficiently and cost effectively. Reconfigurable, adaptable and smart manufacturing paradigms all aim at dealing with these challenges. ElMaraghy et al. keynote paper [5] investigated methods of managing products variety and developing variant-oriented manufacturing systems capable of meeting those requirements in modern manufacturing systems. Manufacturers respond to such fluctuations by controlling product customization and personalization, production volume, manufacturing lead time and product cost and quality. Logical entities such as controls, programs, communication protocols as well as human resources form an important part of the manufacturing enterprise and planning effort. Manufacturing systems are a complicated combination of tools, machines, computers, human workers and managers. Modern manufacturing systems are becoming increasingly complex [6, 7]. The assembly industry is experiencing huge changes with the rapid development of production automation, process control, information technologies and networking. Many manufacturing and assembly enablers emerged to manage the proliferation of product variety and changes in their manufacturing systems [8, 9]. More agile and responsive assembly methods and strategies have to be developed to meet the dynamic requirements of customers and the shortened product lifecycle. More efficient assembly systems must be

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designed in order to remain profitable and competitive [10, 11]. Intelligence and collaboration between machines and humans allow modern systems to evolve and quickly respond to the volatile markets and increasing product variety.

Customers today demand products that can provide easy solutions to their particular needs of manufacturing companies often operate in a dynamic environment driven by fluctuation in market conditions, customer demands, product design and processing technology, and the introduction of new manufacturing systems paradigms.

This paper is not an exhaustive survey, rather it highlights some advances in assembly technologies and systems as a response to changing conditions and increasing variety. Recent developments in joining, material handling, assembly processes, micro assembly, inspection and quality control, robotic assembly, digital and virtual factories, augmented reality, Information and Communication Technology (ICT), planning and control, disassembly and remanufacturing and intelligent and changeable assembly systems are overviewed. In particular, intelligent, reconfigurable and changeable assembly systems are discussed. A typical network of assembly activities is shown in Figure 1. Furthermore, the various advances are grouped in three main areas as shown in Figure 2.

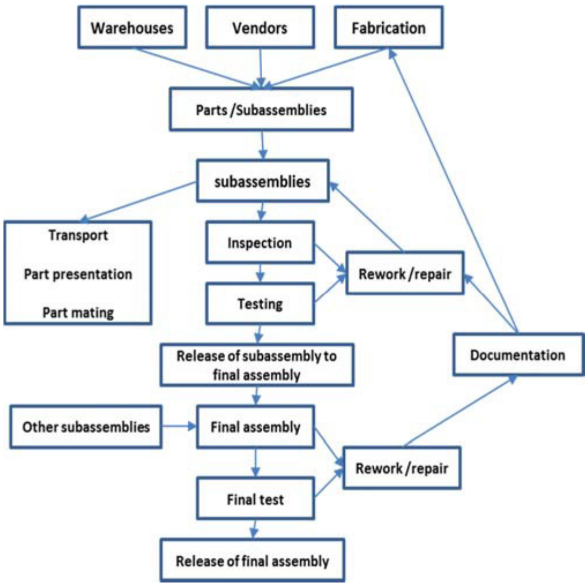


Figure 1 The main processes of assembly [adapted from 1]

2. Advances in assembly processes

2.1. Material handling

The increasing number of product variants, smaller lot sizes, reduced time to market and shorter lifecycles of products have led to increasing demands on automation equipment and concepts. Material handling is a critical component of today's manufacturing processes. Material handling systems are found in almost every manufacturing and distribution company for various goods [12, 13, 14]. A material handling system comprises equipment (conveyors, vehicles, robots, etc.) that transport materials between various locations in the facility. Material handling makes production flow possible, as it gives dynamism to static elements such as materials, products, equipment, layout and human resources. Management and production of customized products requires material handling systems which are flexible and responsive enough to accommodate dynamic and real-time changes in material handling tasks [15]. Material handling management is among many factors that contribute to improve a company's performance as it has direct influence on transit time, resources usage and service levels [16, 17, 18]. The development of new markets increased the manufacturing demands for a large variety of components and final product assemblies increased. This demand growth led to increases in speed and changes in how materials and tools were being handled and transported in order to monitor manufacturing requirements. Conveyors equipped with radio frequency identification (RFID) technology is an example of intelligent conveyors [19]. Such conveyors have a microprocessor, LCD touch screen, reader modules. The conveyor can perform a real-time and synchronous update with the system server.

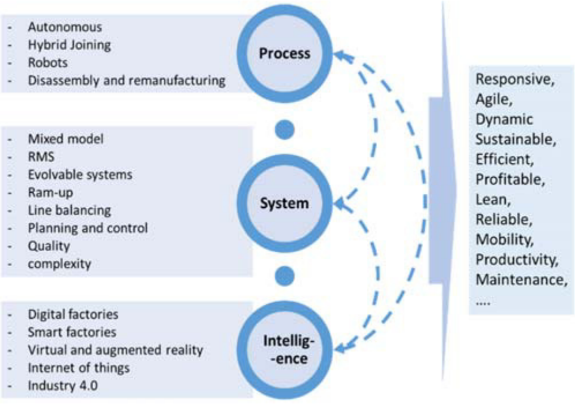


Figure 2 advances in assembly

The unpredictable machine failures, asynchronous among various sections in the assembly line, coupling of sections through finite buffers, and coupling between the production and material handling system increasing the complexity of handling systems [20]. The transport of loads in a complex transport system involving multiple transport equipment requiring a sequence of multiple transport jobs. Efficient and effective models are necessary to evaluate and optimize the material handling system design to improve the flexibility and responsiveness of material handling systems. Online decision and control for job routing plan and resource dispatching in complex transport systems can be controlled using dynamic discrete event controller [15]. The dynamic change of the handling system under various conditions, such as starvation caused by material handling is mathematically described using max-plus algebra [20].

2.2. Robotic assembly

The use of robotic manipulators increases manufacturing productivity. This increase depends on the possibility of reconfiguring or re-programming the robot manipulator to perform various tasks through the use of robots. Camera systems have become a key component of automatic robotic manipulator systems to guide manipulator motion [21]. Cameras which are equipped on mobile robots, enables the robots to observe the workspace and improves the autonomy of these machines. A new generation of ergonomic assist devices, referred to as "intelligent assist systems" or "intelligent assist devices", "collaborative robots" [22], "holonomic manipulators" [23] etc., uses a computer control to improve the movement of heavy items and respond precisely to the operator's interactions. Such devices combine the benefits of human flexibility, intelligence and skills with the advantage of robotic systems capabilities [12, 24]. Collaborative robots are capable of sharing the workspace with the human co-worker and collaborating. These systems integrates advanced force-feedback and programming functions, as well as compliant motion guidance and semi-autonomous functions.

2.3. Autonomous Processes

Autonomy in general means the ability to make decisions without external instructions and performing actions without external forces. Approaches for autonomous systems are for example autonomous production cells, automated guided vehicles, mobile autonomous robots, moving assembly stations, or dexterous robots with intelligent sensors [25, 26, 27]. Autonomy of an equipment implies two characteristics: (1) independence from neighbour equipment and its environment, and (2) the ability to control itself. The first characteristic can be reached by clustering an assembly shop into subsystems and modules with standardised interfaces. The second characteristic requires the decentralisation of the control system according to the granularity of the subsystems and modules [28].

2.4. Disassembly and remanufacturing

Used products are returned to a like-new condition by remanufacturing, thereby recovering most of the added value from original production (including energy, raw materials, and labour) and reducing the environmental impact of the product. Throughout the remanufacturing process, recovered products are systematically disassembled into their basic elements [29]. Products that are difficult to assemble will increase manufacturing cost. Products that are difficult to disassemble will also increase cost as manufacturers are required to recycle products in environmentally friendly methods. Active disassembly is a technical process that enables the mechanical self-disassembly of products by using smart materials in the design of devices, components, adhesives, liquids, layers, etc. These materials are all engineered to react in a predetermined fashion to controlled external stimuli. Active disassembly can allow fast, non-destructive, clean and efficient component separation of complex product assemblies at end-of-life; these components can subsequently be remanufactured or recycled. Active disassembly technologies include hot-wire adhesive release, freezing elements, water-soluble fasteners, shape memory alloy, etc. [30]. Active disassembly is an alternative to conventional dismantling that can significantly reduce remanufacturing cost. The ability to efficiently disassemble is key for remanufacturing because of its significant impact on the remanufacturing success factors of lead times, costs, delivery and quality [31].

Disassembly sequencing performs a major role in the modern design process and is an important tool in concurrent engineering. Disassembly process planning is important for minimizing the resources invested in disassembly and maximizing the level of automation of the disassembly process and the quality of the parts recovered.

3. Advances in assembly systems

The assembly system consists of a network of assembly stations or cells, buffers, transport systems etc. that are clustered into subsystems and modules. In today's environment, assembly systems have to be flexible/changeable in order to adapt quickly to an increasing number of a variety of products and changing demand volume at the same time as achieving quality and productivity [32, 33, 34].

Higher product variety leads to shorter life cycles and smaller production volumes. Therefore, the time spent on assembly planning activities must be reduced [2]. Reconfigurable process planning [35] was introduced to re-configure master plans of existing products to meet the requirements of new products/variants assembly operations instead of generating new plans for new variants from scratch. Kashkoush and ElMaraghy [36] used a genetic algorithm to generate a binary consensus tree that represents a full set of individual assembly sequence trees, and serves as a master assembly sequence for a product family which share a significant number of components and common product structure.

Traditional control systems do not offer higher-level capabilities, such as adaptability, plug-and-play extensibility, interoperability, and openness. Control adaptability and reconfiguration is useful in assembly tasks in dynamically reconfigurable processes or systems across a wide range of operating conditions. It extends the traditional loop control concept to include other functionalities such as supervision, coordination and planning, situation awareness, diagnostics, and optimization. A reconfigurable control system can be used together with a supervisory control switching system (SCSS) to allow the user to match the controller to the particular configuration of robots or machines [37, 38].

3.1. Mixed model assembly systems

Mixed Model assembly is the practice of assembling different models of a product on the same assembly line without changeovers and then sequencing those models in a way that smoothens the demand for upstream components. Mixed model assembly lines are applied in a wide range of industries, e.g. automotive, to mass-produce different models of a common base product. An important decision problem is the sequencing problem, which decides on the sequence in which the models are launched down the assembly line [39, 40, 41]. In a mixed model assembly line, the differentiation point for each product represents the beginning of a unique identity of each product in order to become distinguished from other end products in a product family [42]. The determination of this associated with strategic factors such as capital investment, and inventory costs work in process level (WIP) [3].

3.2. Reconfigurable assembly systems

A reconfigurable assembly system (RAS) is a key component of reconfigurable manufacturing system (RMS). It is one of the most promising paradigms that provides an effective solution to manage change and uncertainties in a complex manufacturing environment [34, 43, 44]. A reconfigurable assembly system is designed at the onset of rapid change in structure, as well as in hardware and software components, in order to quickly adjust product capacity and functionality in response to changes in market or in regulatory requirements. RAS could be the best solution when the products have considerable changes and automations can be implemented economically [45]. Two concepts are implemented in RAS to meet change and uncertainties: modularity and flexibility. RAS consists of modules such as robots and flexible fixtures. These modules are flexible to meet various requirements at the machine or tool level. The RAS modules can be added or removed based on the capacity requirement. The implementation of modularity and flexibility in RAS enhances system capability. Enablers for RAS include: design for ease of assembly (DFA), system modularization, flexible assembly machines, fixtureless assembly processes, material-handling systems, auxiliary machines for reconfiguration, system control, etc. [43].

3.3. Evolvable assembly system

The essence of evolvable assembly system (EAS) resides in the ability of system components to not only adapt to the changing requirements of assembly processes, but also to assist in the evolution of these components in time such that processes may become more robust, and maintenance aspects are supported [46, 47, 48]. Evolvable assembly system consists of self-configuring, highly adaptive and process-oriented components which shift the technological focus from complex, flexible, multi-purpose systems to simpler, dedicated machine modules with embedded controllers that are maintained by a highly distributed control system. Communication between the modules establishes what functionality is required each time a module is added [49]. EAS is based on two principles that lay the groundwork for the system design process [47]: *Principle 1:* the most innovative product design can only be achieved if no assembly process constraints are imposed. This results in fully independent, process selection procedure and may then result in an optimal assembly system methodology; *Principle 2:* evolvable systems must have inherent capability to dynamically adapt to the new products and production scenarios, as well as the emerging system behaviour.

3.4. Ramp – up process

The ramp-up process of assembly systems has a significant impact on both the productivity of those systems and the resulting. A significant saving for manufacturing enterprises and systems integrators can be accomplished by minimizing the ramp-up time. Lack of knowledge capturing and data sharing is recognized as a critical cause for lengthy ramp-up times [50]. It is important for companies to possess knowledge of the ramp-up capability of their production systems in order to plan ramp-ups successfully [5]. Self-learning techniques accelerates the ramp-up process of assembly systems[51]. Such technique uses sensors to allow for a manufacturer specific measure of performance to be applied to the machine's state. Performance indicators, experience recognition, and self-learning software tools provide crucial feedback to the rest of the system to support decision making about future adjustments and accelerating the ramp-up process. Metrics based on the measurable and observable status of the assembly system support decision making [50].

3.5. Line Balancing

Assembly line balancing includes assigning tasks to a set of workstations with consideration for constraints set of precedence relationships, processing time, and the cycle time. The major goal of line balancing is to achieve a similar cycle time at each station [2]. Assembly line balancing problems can be divided into two types [52, 53]: (1) simple assembly line balancing problems which apply to mass-production of one homogeneous product, in paced lines with fixed cycle times, deterministic operation times, with no assignment restrictions other than precedence constraints. (2) generalized assembly line balancing problems which apply to mixed model production with stochastic operation times, workstation paralleling, and assignment restrictions other than precedence constraints. In mixed-model assembly balancing, the different assembly process characteristics of different models result in new problems such as the deviation from the optimal cycle time and model sequencing that do not exist in simple single-model balancing [2]. Numerous methods, dynamic programming, branch and bound, integer programming, etc. are used to solve the assembly line balancing problem [3, 54]. Researchers use hybrid methods such as tabu search (TS) and genetic algorithm (GA) to solve the problem [55] or the combination of a heuristic model and an exact algorithm with intelligent task location or line zone constraints to find a minimum cost solution for the line balancing problem [52].

3.6. Complexity of assembly systems

Many manufacturing and assembly challenges emerged due to the spread of product variety caused by product evolution, increased customisation and changes in manufacturing systems. Increased product variety adds complexity to the manufacturing system and increases production costs. Per ElMaraghy et al. [56], increasing complexity continues to be one of the biggest challenges facing manufacturing today. It is manifested in products and manufacturing processes as well as company structures. These systems operate in an environment of change and uncertainty. The challenges facing industry now are characterized by design complexity that must be matched with a flexible and complex manufacturing system as well as advanced agile business processes. This is particularly true for manufacturers of high value, complex products that are multi-disciplinary in nature. Managing the complexity of assembly and its drivers or sources is essential for improving the efficiency and cost-effectiveness of assembly operations and systems [56, 57, 58]. Samy and ElMaraghy [7, 32] used a code-based complexity metric to measure product assembly complexity [32] and the overall assembly system complexity [7]. The complexity models account for the number, diversity and information content caused by variety. The assembly complexity metrics are used by designers to compare and rationalize various design alternatives and select the least complex assembly design meeting the requirements. Manufacturing systems layout generation and evaluation is challenging and time consuming due to its multi-objective nature and requires extensive data collection, analysis and synthesis. Structural system complexity measuring has received considerable attention, however, the system layout topology and its effect on structural complexity were not considered. ElMaraghy et al [6] developed a new method to assess the structural complexity of manufacturing system layout. An overall complexity index, combining those individual indices, represents the structural complexity of the system layout and measures information content which increases or decreases the difficulty of making decisions regarding the flow of material in the system layout.

3.7. Advances in inspection and quality control

Quality of assembly may be defined by how well the product conforms to the design specification. Quality of assembly is a complex issue and can be assured in many ways. Methods of quality assurance for assembly include: tolerance design and worst-case analysis [59], statistical analysis, online quality assurance methods [60]. Inspection using traditional coordinate measuring machines (CMM) is time consuming, while modern manufacturing seeks a rapid surface inspection using a 3D sensor. The focus of the new technologies including sensor accuracy, resolution, system efficiency, and system cost. A robot-aided sensing system can automatically allocate sensor viewing points, measure the freeform part surface, and generate an error map for quality control. Multiple robots can be adopted to accomplish the goal efficiently for a complex vision task in a large-scale environment. This requires a good scheme of system integration. Tools (e.g. neural network) are used to analyze collected data and to intelligently schedule both preventive and corrective quality improving operations as well as dynamic diagnosis of machine faults [60].

4. Intelligent systems

Today, there is a great deal of embedded intelligence in devices, systems, and products. Smarter assets and devices have essentially become data centers driving intelligence across the enterprise. Internet of things (IOT) refers to a networked interconnection of objects whose purpose is to make all things communicable [21, 61]. Internet of things enables objects to communicate things about themselves like what they are, where they are, their status, condition, and so forth. If properly employed, the interconnected objects can decrease the boundaries between the physical and digital worlds and enable the system to make smarter and more timely decisions [61].

4.1. Virtual factories and augmented reality

The virtual factory focuses on the top level factory routing between various work cells in the virtual factory environment. The virtual factory environment (VFE) design includes the ability to interact with users through a user interface, perform a range of analysis and compare the assembly alternatives that can reduce the overall assembly time as well as support assembly level re-design of individual work cells [62].

Virtual reality (VR) is an artificial environment with important features such as immersion, interaction and imagination, and provides multiple sensorial channels including visual, auditory, haptic, smell, and taste feedback. With the recent advances in computer graphics, VR is becoming a popular technology in many industrial applications that require a realistic computer–human interface [63]. VR is gaining popularity in manufacturing as an engineering design tool and is increasingly used in the product realization process as a digital test-bed for early product development [64, 65]. The designer can visualize and interact with 3D models of complex products using haptics technology to interact with virtual objects using natural and intuitive human motions to feel the physical contacts, friction, gravity, and collision detection, and identify assembly-related problems such as accessibility, reachability, ergonomics, sequence and path, etc. [64, 66, 67]. The main prerequisite for nearly all VR applications is data extraction from a CAD system. CAD systems are used to model physical objects, while VR systems use scene graphs to animate the motion and interaction of CAD models [10].

A "virtual factory" is a cross-reality environment designed for simulation, visualization, and collaboration, using a set of interlinked, real-time 3D and 2D layers of information dealing with the factory and its processes. Collaborative applications can be used for tasks such as remote factory observation, machine monitoring, process/workflow monitoring and analysis, virtual inspections, mobile/virtual teleportation, augmented reality, education and training of employees, visitor tours, and inventory tracking [68]. A typical virtual factory integrated platform is composed of a database system, a simulation system, and a three-dimensional scene system. Each subsystem can communicate information with others to realize the integration of the total platform. Users can set different instructions regarding scheduling and process control in the virtual factory through the input-interface [69].

Augmented reality (AR) technologies allow the user to see the real environment with virtual objects superimposed upon the real world [10]. AR is potentially cheaper and a more realistic tool for assembly design than VR. AR systems can utilize established techniques in VR and evaluate the assembly more realistically with a combination of virtual and real objects in the actual workspace.

4.2. Smart factories

The smart factory concept can be perceived as new technology which enables the virtual plant environment to implement integration of methods and tools available on different levels for planning and testing products and the related production and operative control of the factory. It can also be seen as enterprise and information strategy managing and collaborating processes of factories in global networks. The integration of tools for design, planning, simulation, communication and control is required on all planning and factory levels [70, 71]. Digital factory technology runs through the whole product lifecycle product design, manufacturing process, and production planning can be simulated, analyzed and optimized in digital factory through data integration with other information systems [71].

Cyber-physical systems (CPS) - embedded systems with decentralized control intelligence - can establish communication through open networks based on internet protocols [72]. These cyber physical systems have sensors and actors and can make decisions based on their own intelligence and partially adapt to changing conditions [73]. All production-related data, on order and material streams, costs and product quality from the various IT systems and production sectors and the shop floor system, are merged and made available in real time [74, 75]. Design, planning, production execution and services are collectively implemented in an exciting way. Knowledge and information are shared across various departments in a dynamic environment, leading to shortening the innovation cycle, increasing productivity, minimizing risk, and enhancing human work experience [61, 76]. A prototype architecture for assembly-oriented cyber physical systems includes embedded systems, sensing technology and networked connectivity. Embedded systems provide devices with intelligence while sensors provides perception and networked connectivity gives them the ability to communicate. A decision support system can process the data and generate operation orders according to certain rules. It can also generate alarms for equipment failure or short supply of materials [77].

Radio frequency identification (RFID) is a non-contact automatic identification technology. It can automatically identify targets and obtain relevant data through radio-frequency signals. The RFID technology is currently expanding to the manufacturing sector, partly due to the rapid reduction in costs of readers and tags over the last few years. The technology has rapidly progressed in recent years in the development of high-performance readers, tags, and middleware. The value of RFID is evident in transforming real-time information collected by RFID into intelligence. The real-time information is used to improve the timeliness and efficiency of the decision-making processes [78].

In “smart factory”, all objects including machines, devices and products are smart and networked and can communicate with each other. They have sufficient computing power and communication capabilities to allow for autonomous operation. The smart factory is a representative of the fourth industrial revolution and a fundamental shift in operating practices that will change the way manufacturing operates [79]. A true network era is enabled by smart networked devices. The fourth dimension follows the introduction of mechanical production facilities powered by water and steam, the introduction of mass production based on the division of labour powered by electrical energy, and finally, the introduction of electronics and IT, for further automation of production.

Developments affecting factory of the future include [80]:

- Smart devices: devices with a built-in intelligence networked with other devices via wireless protocols and can operate interactively and autonomously.
- Everything is networked: everything has an IP address and can communicate in a very reliable networks.
- Mobility of devices: independent devices with standard interface to have the ability to work anywhere any time.
- Standards must emerge: standard devices and equipment, standard software, and standard representations are necessary for networking and mobility.

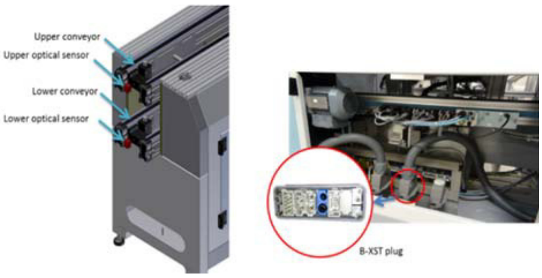
Although the vision for future factories exists, the following problem should be considered [80]:

- Adjusting existing devices and developing new devices for the industrial use. The devices should be produced according to defined standards at low prices.
- Identifying the various levels of aggregation of services on the organisation as a whole.
- Data integration to allow new planning methods and develop comprehensive device and services models.
- Considering safety and security issues to avoid risks of criminal attacks in the mobile and wireless devices.
- The role of human in the highly automated environment.

5. Changeable and Reconfigurable Assembly Systems

The iFactory in the Intelligent Manufacturing Systems (IMS) Center at the University of Windsor, Canada is a state-of-the-art transformable factory for products assembly [81]. It consists of modules that can be easily reconfigured to change the system layout and functionality. Its unique drive technology, control, interfaces, and modularity are essential for developing, testing, and demonstrating the innovative physical and logical enablers of change and products variety management such variant-oriented orders processing, process plans, production plans and schedules. All system modules are equipped with topology feedback so that the control system automatically recognizes the line configuration. The continuous material-flow is achieved within each module using two levels conveyor built into each system module for transportation. Workpieces are transported via carriers to the next cell on the upper level and transported back on the lower level. The cells are equipped with two optical sensors used to identify their “neighbour”. The upper level sensors send an on/off signal to identify the existence of a neighbouring station. The lower level sensors retrieve the identification of the station. Each cell passes the signals to the neighbouring module or to the SCADA control system. The stations are connected with an Ethernet network, and communication is realized using the Profinet protocol. The Ethernet cable is also fed in with the multifunctional energy coupling which is equipped with 24V power supply emergency stop, power supply, potential equalization, compressed air supply, and Ethernet.

The modularity of the iFactory aids in realizing a diverse range of system configurations for typical assembly systems which can be created and expanded by adding/removing and re-distributing modules in short time as all modules are mobile.



(a) (b)

Figure 3 (a) Two layers conveyors and optical sensors (b) Multifunctional energy coupling

5.1. Original production line

The first iFactory system configuration is used for assembling a desk set as shown in Figure 4(a). It has a short cup, long cup and built in sticky notes holder. The corresponding system consist of an automatic storage/retrieval system, a robotic assembly cell, two termination cells, and two conveyor modules as shown in Figure 4(b).

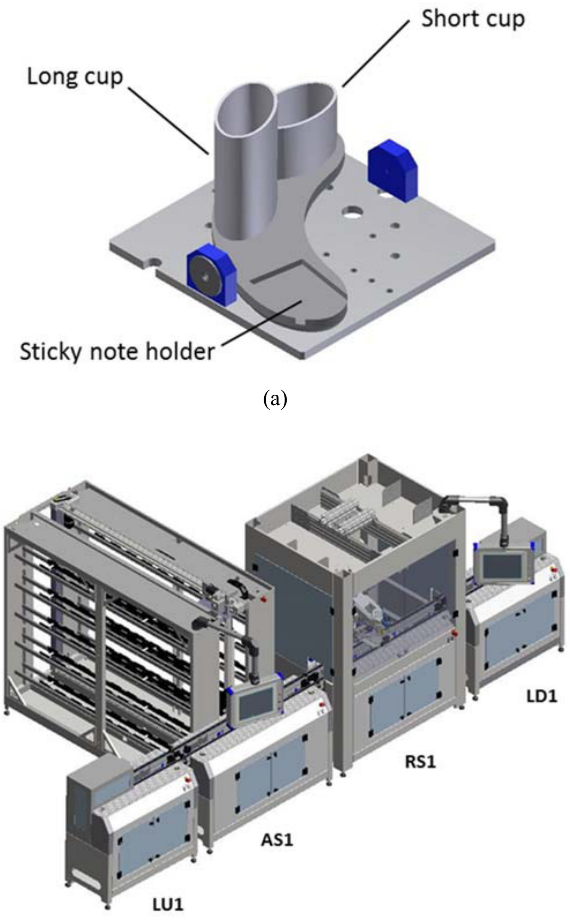
All cells are networked using the SCADA system (Figure 5(a)). The SCADA system includes a professional PC with control cabinet. The 'Pathfinder' automatically detects the assembled i-Factory system topology as shown in Figure 5(b). Device drivers, human machine interface and database interface are included. The SCADA system allows complete supervising, monitoring and operating of the iFactory, in addition to orders input.

A package (carrier with RFID, palette and workpiece) is identified at the AS/RS station, and transported to the robot assembly cell to assemble the two cups. The identification data of the workpiece are stored directly on the workpiece carrier. The RFID technology built-in the workpiece holders enables tracking of each stage of the production process. Desk set modules are fed to the robot via two trays. The carrier is released and transported back to the AS/RS station after assembling the cups. The line-up (LU) termination cell moves workpiece carriers with a pneumatic lift from the lower to the upper conveyor system. The line-down (LD) termination cell moves workpiece carriers with a pneumatic lift from the upper to the lower conveyor system. These cell have to be placed at the start and every end of the system respectively.

5.2. New production line

A new desk set is introduced as shown in Figure 6 (a). It has a short cup, long cup, cover plate, and temperature indicator/clock. The production line should be reconfigured to include two new stations: a vision inspection station and a manual assembly station. The vision station is required to check the cover plate alignment. The manual station is used to fix the rejected parts (if needed) and assemble the thermometer/clock modules. The new system configuration is shown in Figure 6 (b). It consists of an automatic storage/retrieval system, a vision cell, a manual assembly cell, a robotic assembly cell, three termination cells, a branching cell, and two bi-level conveyor modules. The new system can easily be configured in short time by adding the new modules to the initial configuration (Figure 6(b)). The SCADA system 'Pathfinder' automatically detects the reconfigured i-Factory production-line (Figure 7) and controls it accordingly.

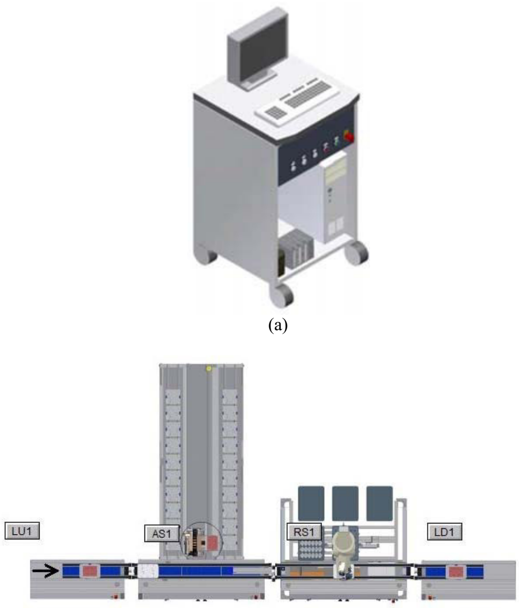
A carrier with a palette and a workpiece, at the AS/RS station, is identified, retrieved and transported to the vision cell to check the alignment of the cover plate, and the robot assembly cell assembles the two cups. The carrier is released and transported to the manual station to assemble the thermometer after assembling the cups. The workpiece identification data are stored directly on the workpiece carrier at the manual assembly cell. Data is read via RFID technology at the cell stop position. The assembly steps are monitored and the operator has to acknowledge the assembly via the touch panel. The complete assembly is then transported back to the ASRS station (process finished).



(a)

(b)

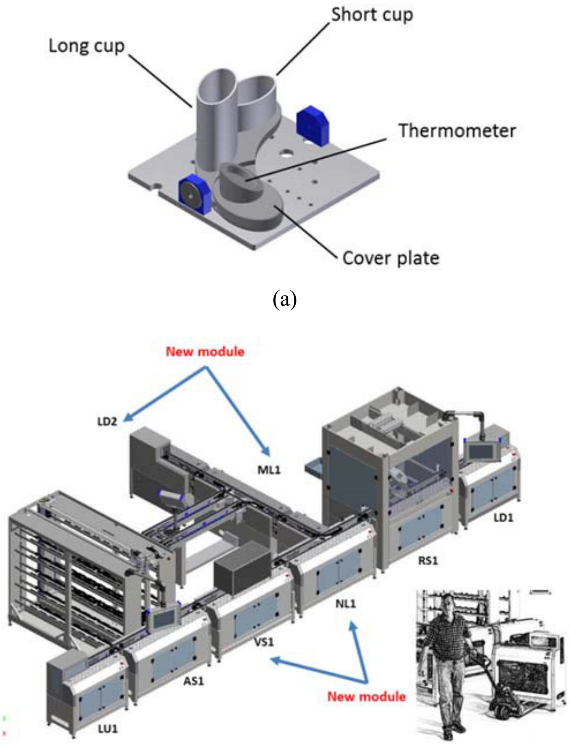
Figure 4 (a) Original product (b) Original production line (LU = Line up termination cell, AS = Automated storage/retrieval cell, RS = Robot assembly cell, LD = Line down termination cell)



(a)

(b)

Figure 5 (a) SCADA System, (b) System topology



(a)

(b)

Figure 6 (a) New product (b) New production line (LU = Line up termination cell, AS = Automated storage/retrieval cell, VS = Vision cell, NL = Branch cell, ML = Manual assembly cell, LD = Line down termination cell, RS = Robot assembly cell)

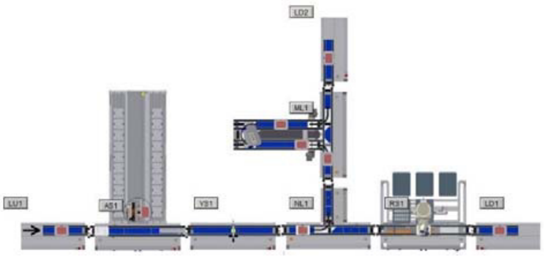


Figure 7 System topology

6. Summary and Conclusions

An overview of important advances in assembly technologies and systems was presented. Flexible, adaptable, reconfigurable and changeable assembly systems paradigms have evolved to respond to frequent changes in products and production volume, and reduce time to market. Research into effective systems integration, modularization and standardization, plug-in capabilities and embedded intelligence is needed. Mobile robots, collaborative robots, and intelligent assist systems enable the dynamic change in advanced assembly systems. Reconfigurable and real-time control of such systems needs further research. Remanufacturing and active disassembly are receiving more attention to promote sustainability. Although modern assembly systems increasingly use automation, human-centered assembly systems are important. Changeability and reconfiguration calls for more emphasis on quality assurance and error proofing is critical in view of their increasingly complexity.

Digital and smart factories are becoming increasingly important as prerequisites for the anticipated fourth industrial revolution (Industry 4.0). The automation and control require a networking technology to enable sensors communication throughout the plant and the enterprise. Digital manufacturing, intelligent devices, systems, and automation are necessary and must be integrated into one world via IT systems to optimize the use, capacity and responsiveness of manufacturing systems. Important research topics include modeling of virtual factories, internet of things and cyber physical systems, and networking. Integration of various CAD models from various CAD systems and different file formats is challenging in the virtual world where reliability, ease of use, and training are a challenge.

Finally, co-development of products and manufacturing / assembly systems is essential to prolong the life of such expensive systems for use in many products variants and generations and ensure their economic sustainability.

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References

[1] Whitney, D.E., 2004, *Mechanical Assemblies: Their Design, Manufacturing, and Role in Product Development*, New York, Oxford University Press.

[2] Hu, S.J., Ko, J., Weyand, L., ElMaraghy, H., Lien, T.K., Koren, Y., Bley, H., Chryssolouris, G., Nasr, N., Shpitalni, M., 2011, *Assembly system design and operations for product variety,* CIRP Annals - Manufacturing Technology, 60/2:715-733.

[3] Algeddawy, T., ElMaraghy, H., 2010, *Design of single assembly line for the delayed differentiation of product variants,* Flexible Services and Manufacturing Journal, 22/3-4:163-182.

[4] Zhila Pirmoradi, G. Gary Wang, Simpson, T.W., 2014, *A Review of Recent Literature in Product Family Design and Platform-Based Product Development*, in *Advances in Product Family and Product Platform Design*, T.W. Simpson,J.R. Jiao,Z. Siddiqueand K. Hölttä-Otto, Editors, Springer, New York, 1-46.

[5] ElMaraghy, H., Schuh, G., ElMaraghy, W., Piller, F., Schonsleben, P., Tseng, M., Bernard, A., 2013, *Product variety management,* CIRP Annals - Manufacturing Technology, 62/2:629-652.

[6] ElMaraghy, H., AlGeddawy, T., Samy, S.N., Espinoza, V., 2014, *A model for assessing the layout structural complexity of manufacturing systems,* Journal of Manufacturing Systems, 33/0:51 -64.

[7] Samy, S.N., ElMaraghy, H., 2012, *A model for measuring complexity of automated and hybrid assembly systems,* Int. J. of Advanced Manufacturing Technology, 62/5:813 - 833.

[8] ElMaraghy, H., 2009, *Changing and Evolving Products and Systems - Models and Enablers*, in *Changeable and Reconfigurable Manufacturing Systems*, H. ElMaraghy, Editor, Springer-Verlag: London, 25-45.

[9] Li, S., Wang, H., Hu, S.J., 2013, *Assembly system configuration design for a product family*, *41st North American Manufacturing Research Conference 2013, NAMRC 2013, June 10, 2013 - June 14, 2013*, Madison, WI, United states: Society of Manufacturing Engineers, 9-20.

[10] Leu, M.C., ElMaraghy, H.A., Nee, A.Y.C., Ong, S.K., Lanzetta, M., Putz, M., Zhu, W., Bernard, A., 2013, *CAD model based virtual assembly simulation, planning and training,* CIRP Annals - Manufacturing Technology, 62/2:799-822.

[11] Matt, D.T., 2013, *Design of a scalable assembly system for product variety: A case study,* Assembly Automation, 33/2:117-126.

[12] Gambao, E., Hernando, M., Surdilovic, D., 2012, *A new generation of collaborative robots for material handling,* Gerontechnology, 11/2:368.

[13] Kitaaki, Y., Haraguchi, R., Shiratsuchi, K., Domae, Y., Okuda, H., Noda, A., Sumi, K., Fukuda, T., Kaneko, S., Matsuno, T., 2011, *A robotic assembly system capable of handling flexible cables with connector*, *2011 IEEE International Conference on Mechatronics and Automation (ICMA 2011), 7-10 Aug. 2011*, Piscataway, NJ, USA: IEEE, 893-7.

[14] Yu, S., Gil, M., 2012, *Manipulator handling device for assembly of large-size panels,* Assembly Automation, 32/4:361-372.

[15] Joe, Y.Y., Peen, G.O., L., L.F., 2014, *Multi-commodity flow dynamic resource assignment and matrix-based job dispatching for multi-relay transfer in complex material handling systems (MHS),* J Intell Manuf Journal of Intelligent Manufacturing, 25/4:681-697.

[16] Vieira, G.B.B., Pasa, G.S., Borsa, M.B.N.d.O., Milan, G.S., Pandolfo, A., 2011, *MATERIALS HANDLING MANAGEMENT:A CASE STUDY,* Journal of Operations and Supply Chain Management, 4/2:19-30.

[17] Wanstrom, C., Medbo, L., 2009, *The impact of materials feeding design on assembly process performance,* Journal of Manufacturing Technology Management, 20/1:30-51.

[18] Krefft, M., Last, P., Budde, C., Maass, J., Hesselbach, J., Wahl, F.M., 2007, *Improvement of parallel robots for handling and assembly tasks,* Assembly Automation, 27/3:222-230.

[19] Zhu, C.-p., Wang, Z., Deng, J.-x., Gu, H., Shan, M.-l., Han, Q.-b., Yu, H.-z., Zhang, S., 2010, *Design of an Intelligent Book Conveyor based on RFID*, *Information Science and Engineering (ICISE), 2010 2nd International Conference on*, 1993-1996.

[20] Chang, Q., Pan, C., Xiao, G., Biller, S., 2013, *Integrated Modeling of Automotive Assembly Line With Material Handling,* Journal of Manufacturing Science and Engineering, 135/1:011018-011018.

[21] Shengyong, C., Youfu, L., Ngai Ming, K., 2011, *Active vision in robotic systems: A survey of recent developments,* International Journal of Robotics Research, 30/11:1343-77.

[22] Surdilovic, D., Schreck, G., Schmidt, U., 2010, *Development of collaborative robots (COBOTS) for flexible human-integrated assembly automation*, *Joint 41st International Symposium on Robotics, ISR 2010 and 6th German Conference on Robotics 2010, ROBOTIK 2010, June 7, 2010 - June 9, 2010*, Munich, Germany: VDE Conference Department, 90-97.

[23] Zhijun, L., Ge, S.S., Aiguo, M., 2007, *Adaptive robust motion/force control of holonomic-constrained nonholonomic mobile manipulators,* IEEE Transactions on Systems, Man and Cybernetics, Part B (Cybernetics), 37/3:607-16.

[24] Krüger, J., Bernhardt, R., Surdilovic, D., Spur, G., 2006, *Intelligent Assist Systems for Flexible Assembly,* CIRP Annals - Manufacturing Technology, 55/1:29-32.

[25] Bruyninckx, H., Lefebvre, T., Mihaylova, L., Staffetti, E., De Schutter, J., Xiao, J., 2001, *A roadmap for autonomous robotic assembly*, *Proceedings of the 2001 IEEE International Symposium on Assembly and Task Planning (ISATP2001) Assembly and Disassembly in the Twenty-first Century, 28-29 May 2001*, Piscataway, NJ, USA: IEEE, 49-54.

[26] Hamner, B., Koterba, S., Shi, J., Simmons, R., Singh, S., 2010, *An autonomous mobile manipulator for assembly tasks,* Autonomous Robots, 28/1:131-49.

[27] Jerbic, B., 2002, *Autonomous robotic assembly using collaborative behavior based agents,* International Journal of Smart Engineering System Design, 4/1:11-20.

[28] Scholz-Reiter, B., Freitag, M., 2007, *Autonomous Processes in Assembly Systems,* CIRP Annals - Manufacturing Technology, 56/2:712-729.

[29] Li, W., Xia, K., Lu, B., Chao, K.M., Gao, L., Yang, J.X., 2013, *A Distributed Service of Selective Disassembly Planning for Waste Electrical and Electronic Equipment with Case Studies on Liquid Crystal Display*, in *Cloud Manufacturing*, W. LiJ. Mehnen, Editors, Springer London, 23-47.

[30] Chiodo, J., Jones, N., 2012, *Smart materials use in active disassembly,* Assembly Automation, 32/1:8-24.

[31] Chiodo, J.D.I.W.L., 2014, *Use of active disassembly technology to improve remanufacturing productivity: automotive application,* International Journal of Computer Integrated Manufacturing International Journal of Computer Integrated Manufacturing, 27/4:361-371.

[32] Samy, S.N., ElMaraghy, H., 2010, *A model for measuring products assembly complexity,* Int. J. of Computer Integrated Manufacturing, 23/1015-1027.

[33] Rosati, G., Faccio, M., Carli, A., Rossi, A., 2011, *Convenience analysis and validation of a fully flexible assembly system*, *2011 IEEE 16th Conference on Emerging Technologies & Factory Automation, 5-9 Sept. 2011*, Piscataway, NJ, USA: IEEE, 8 pp.

[34] Yan, H., Yin, Y.-h., Yu, J.-f., 2005, *Study on the reconfiguration of the assembly module in the reconfigurable assembling system,* Industrial Engineering and Management, 10/2:10-14.

[35] Azab, A., ElMaraghy, H., 2007, *Mathematical Modeling for Reconfigurable Process Planning,* CIRP Annals - Manufacturing Technology, 56/1:467-472.

[36] Kashkoush, M.E.H., 2014, *Consensus tree method for generating master assembly sequence,* Prod. Eng. Res. Devel. Production Engineering, 8/1-2:233-242.

[37] Yang, C., ElMaraghy, H., Azab, A., 2007, *Reconfigurable control structure for robots in assembly,* Journal of Intelligent & Robotic Systems, 50/4:419-39.

[38] Gao, T., Mu, G., Pan, L., Xie, Z., 2012, *Research on and design of assembly line monitor and control system based on PC*, *2012 International Conference on Industrial Design and Mechanical Power, ICIDMP 2012, July 10, 2012 - July 11, 2012*, Huangshan, China: Trans Tech Publications, 551-554.

[39] Boysen, N.S.A.W.N., 2011, *Resequencing of mixed-model assembly lines survey and research agenda*, Jena, Univ., Wirtschaftswiss. Fak.

[40] Rekiek, B., De Lit, P., Delchambre, A., 2000, *Designing mixed-product assembly lines,* IEEE Transactions on Robotics and Automation, 16/3:268-80.

[41] Venkatesh, J.V.L., Dabade, B.M., 2010, *Performance evaluation of mixed model assembly lines,* International Journal of Manufacturing Technology and Management, 21/1-2:176-193.

[42] Algeddawy, T., Elmaraghy, H., 2010, *Assembly systems layout design model for delayed products differentiation,* International Journal of Production Research, 48/18:5281-5305.

[43] Bi, Z.M., Lihui, W., Lang, S.Y.T., 2007, *Current status of reconfigurable assembly systems,* International Journal of Manufacturing Research, 2/3:303-28.

[44] Jianfeng, Y., Yuehong, Y., Xinjun, S., Zhaoneng, C., 2003, *Modelling strategies for reconfigurable assembly systems,* Assembly Automation, 23/3:266-72.

[45] Frangieh, T., Stroop, R., Athanas, P., Cervero, T., 2012, *A Modular-Based Assembly Framework for Autonomous Reconfigurable Systems*, *Reconfigurable Computing: Architectures, Tools and Applications. 8th International Symposium, ARC 2012, 19-23 March 2012*, Berlin, Germany: Springer Verlag, 314-19.

[46] Lohse, N., Ratchev, S., Barata, J., 2006, *Evolvable assembly systems - on the role of design frameworks and supporting ontologies*, *2006 IEEE International Symposium on Industrial Electronics, 9-13 July 2006*, Piscataway, NJ, USA: IEEE, 3375-80.

[47] Semere, D., Barata, J., Onori, M., 2007, *Evolvable assembly systems: Developments and advances*, *IEEE International Symposium on Assembly and Manufacturing, ISAM 2007, July 22, 2007 - July 25, 2007*, Ann Arbor, MI, United states: Inst. of Elec. and Elec. Eng. Computer Society, 282-287.

[48] Semere, D., Onori, M., Maffei, A., Adamietz, R., 2008, *Evolvable assembly systems: Coping with variations through evolution,* Assembly Automation, 28/2:126-133.

[49] Bogue, R., 2012, *Europe fights back with advanced manufacturing and assembly technologies,* Assembly Automation, 32/4:312-317.

[50] Doltsinis, S.C., Ratchev, S., Lohse, N., 2013, *A framework for performance measurement during production ramp-up of assembly stations,* European journal of operational research, 229/1:85-94.

[51] Oates R, S.D.R.S.t.I.P.A.S.I., 2012, *Accelerated ramp-up of assembly systems through self-learning,* IFIP Advances in Information and Communication Technology IFIP Advances in Information and Communication Technology, 371 AICT/175-182.

[52] Padron, M., Maria de los, A.I., Resto, P., Mejia, H.P., 2009, *A methodology for cost-oriented assembly line balancing problems,* Journal of Manufacturing Technology Management, 20/8:1147-1165.

[53] Scholl, A.B.C., 2006, *State-of-the-art exact and heuristic solution procedures for simple assembly line balancing,* European Journal of Operational Research European Journal of Operational Research, 168/3:666-693.

[54] Rada-Vilela, J., Chica, M., Cordon, O., Damas, S., 2013, *A comparative study of multi-objective ant colony optimization algorithms for the time and space assembly line balancing problem,* Applied Soft Computing Journal, 13/11:4370-4382.

[55] Suwannarongsri, S., Limnararat, S., Puangdownreong, D., 2007, *A new hybrid intelligent method for assembly line balancing*, *2007 IEEE International Conference on Industrial Engineering and Engineering Management, 2-4 Dec. 2007*, Piscataway, NJ, USA: IEEE, 1115-19.

[56] ElMaraghy W, ElMaraghy H, Tomiyama T, Monostori L. (2012). *Complexity in Engineering Design and Manufacturing* (Keynote paper). CIRP Annals Manufacturing Tech. 61(2): 793 – 814.

[57] Samy, S.N., ElMaraghy, H., 2012, *Complexity Mapping of the Product and Assembly System,* Assembly Automation, 32/2:135-151.

[58] Orfi, N., Terpenny, J., Sahin-Sariisik, A., 2011, *Harnessing product complexity: Step 1establishing product complexity dimensions and indicators,* Engineering Economist, 56/59-79.

[59] Fischer, B.R. *Mechanical tolerance stackup and analysis*. 2011; Available from: http://www.crcnetbase.com/isbn/978-1-4398-1572-4.

[60] Feldmann, K., Holzmann, R., Schaller, A., 2001, *Accompanying quality assurance with intelligent process coordination*, *Proceedings of SMTA International, 30 Sept.-4 Oct. 2001*, Edina, MN, USA: Surface Mount Technol. Assoc, 457-65.

[61] Hessman, T., 2013, *The Dawn of the Smart Factory,* Industry Week, 262/2:14-19.

Nikolaus, K., 2013, *Industry 4.0: Building the Nuts and Bolts of Self-Organizing Factories,* Siemens: Pictures of the Future, Spring/19-22.

[81] http://www.festo.com/

[62] Cecil J., Huber J., Gobinath N., J., J., 2011, *A virtual factory environment to support process design in micro assembly domains,* Comput.-Aided Des. Appl. Computer-Aided Design and Applications, 8/1:119-127.

[63] Wang, Q.H., Li, J.R., Gong, H.Q., 2006, *A CAD-linked virtual assembly environment,* International Journal of Production Research, 44/3:467-486.

[64] Xia, P.L.A.M.R.M.T., 2013, *A review of virtual reality and haptics for product assembly (part 1): rigid parts,* ASSEMBLY AUTOMATION - BEDFORD THEN BRADFORD-, 33/1:68-77.

[65] Xia, P.L.A.M.R.M.T., 2013, *A review of virtual reality and haptics for product assembly: from rigid parts to soft cables,* ASSEMBLY AUTOMATION -BEDFORD THEN BRADFORD-, 33/2:157-164.

[66] Ng, L.X., 2013, *Integrated product design and assembly planning in an augmented reality environment,* Assembly Automation Assembly Automation, 33/4:345-359.

[67] Jun, Y., Liu, J., Ning, R., Zhang, Y., 2005, *Assembly process modeling for virtual assembly process planning,* International Journal of Computer Integrated Manufacturing, 18/6:442-451.

[68] Back M., Childs T., Dunnigan A., Foote J., Gattepally S., Liew B., Shingu J., Vaughan J., 2010, *The Virtual Factory: Exploring 3D worlds as industrial collaboration and control environments,* IEEE Virtual Reality, 257-258.

[69] Zhou, Z., Feng, Y., Zhu, F., Rong, G., 2011, *Virtual factory integrated manufacturing system for process simulation and monitoring,* IFAC Proc. Vol. (IFAC-PapersOnline) IFAC Proceedings Volumes (IFAC-PapersOnline), 18/PART 1:5219-5224.

[70] Kuhn, W., 2006, *Digital factory - Simulation enhancing the product and production engineering process*, *2006 Winter Simulation Conference, WSC, December 3, 2006 - December 6, 2006*, Monterey, CA, United states: Institute of Electrical and Electronics Engineers Inc., 1899-1906.

[71] Ting, Y., Dinghua, Z., Bing, C., Shan, L., 2008, *Research on plant layout and production line running simulation in digital factory environment*, *2008 Pacific-Asia Workshop on Computational Intelligence and Industrial Application, PACIIA 2008, December 19, 2008 - December 20, 2008*, Wuhan, China: Inst. of Elec. and Elec. Eng. Computer Society, 588-593.

[72] Schlick, J., 2012, *Cyber-physical systems in factory automation - Towards the 4th industrial revolution*, *Factory Communication Systems (WFCS), 2012 9th IEEE International Workshop on*, 55-55.

[73] Verl, A., Lechler, A., Schlechtendahl, J., 2012, *Glocalized cyber physical production systems,* Production Engineering - Research and Development, 6/6:643-9.

[74] James, T., 2012, *Smart factories,* Engineering & Technology, 7/6:64-7.

[75] Ghonaim, W., Ghenniwa, H., Weiming, S., 2011, *Towards an agent oriented smart manufacturing system*, *2011 15th International Conference on Computer Supported Cooperative Work in Design (CSCWD), 8-10 June 2011*, Piscataway, NJ, USA: IEEE, 636-42.

[76] Davis, J., Edgar, T., Porter, J., Bernaden, J., Sarli, M., 2012, *Smart manufacturing, manufacturing intelligence and demand-dynamic performance,* Computers & Chemical Engineering, 47/145-56.

[77] Dong, J., Xiao, T., Zhang, L., 2012, *A prototype architecture for assembly-oriented cyber-physical systems*, *Asia Simulation Conference, AsiaSim 2012, October 27, 2012 - October 30, 2012*, Shanghai, China: Springer Verlag, 199-204.

[78] Gwon, S.-h.O.S.-C.H.N.H.S.-k., 2011, *Advanced RFID application for a mixed-product assembly line,* International Journal of Advanced Manufacturing Technology, 56/1-4:1-4.

[79] Nikolaus, K., 2013, *Industry 4.0: Building the Nuts and Bolts of Self-Organizing Factories,* Siemens: Pictures of the Future, Spring/19-22.

[80] Zuehlke, D., 2008, *SmartFactory – from Vision to Reality in Factory Technologies*, *The International Federation of Automatic Control, July 6-11, 2008*, Seoul, Korea,