Adaptability in Smart Manufacturing Systems

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***Abstract*—Adaptability and reconfigurability of the production system are two key enablers to address global competition and a constantly evolving demand. Adaptive and smart manufacturing systems, realized by a variable number of heterogeneous production Smart Components with specialized capabilities, is one promising approach to guarantee a high degree of adaptability to ever changing demand. This paper presents a realization of a smart manufacturing system based on a multi-agent system approach, discusses its values and drawbacks, and presents possible improvements on the conceptual realization.**

Keywords—smart manufacturing systems; production smart components; adaptability; reconfigurability.

I. Introduction

Rapid changing product portfolios and continuously evolving process technologies require manufacturing systems that are themselves easily upgradeable, into which new technologies and new functions can be readily integrated [1]. This demands increased productivity through highly optimized production processes, creating the need for novel manufacturing control systems able to cope with the increased complexity required to manage product and production variability and disturbances, effectively and efficiently [2], and to implement agility, flexibility and reactivity in mass customized manufacturing.

Increasingly, traditional top-down and centralized process planning, scheduling, and control mechanisms are becoming insufficient to respond to constant changes in these high-mix low-volume production environments [3]. These traditional centralized hierarchical approaches limit the adaptability [4], contribute to reduce the resilience of the system, as well as to reduce the flexibility of planning and contribute to a corresponding increase in response overheads [5]. The ability of a manufacturing system, at all of the functional and organizational levels, to reconfigure itself in order to quickly adjust production capabilities and capacities in response to sudden changes in the market or in the regulatory environment is nowadays a major requirement.

This paper presents a realization of a smart manufacturing system based on a multi-agent system framework to implement the concept of adaptive and reconfigurable factory. Its contributions and limitations are discussed, along with the roadmap for future improvements.

The paper is structured as follows. After presenting the motivation and objectives, Section 2 frames the problem and presents related work. In Section 3, the overall approach is presented and Section 4 presents the multi-agent system-based realization. Section 5 discusses the results, as well as future improvements, and Section 6 presents the conclusions.

II. Related Work

The manufacturing enterprises of the 21st century are in an environment in which market demand is frequently changing, new technologies are continuously emerging, and competition is global. Manufacturing strategies should therefore shift to support global competitiveness, new product innovation and customization, and rapid market responsiveness. The next generation of manufacturing systems will thus be more strongly time-oriented (or highly responsive), while still focusing on cost and quality. Such manufacturing systems will need to satisfy a number of fundamental requirements, including [6]: Full integration of heterogeneous software and hardware systems within an enterprise, or across a supply chain; Open system architecture to accommodate new subsystems (software, hardware, *peopleware*) or dismantle existing subsystems "on the fly"; Efficient and effective communication and cooperation among different elements (units, lines, cells, equipment) within an enterprise and among enterprises; Embodiment of human factors into manufacturing systems; Quick response to external order changes and unexpected disturbances from both internal and external manufacturing environments; Fault tolerance both at the system level and at the subsystem level so as to detect and recover from system failures and minimize their impacts on the overall performance. Some possible approaches to fulfil these requirements are presented in the next sections.

A. Networked Factories and equipment virtualization

Modern Industries have a continuous need to satisfy their markets at better costs in order to keep their competitive edge. This simple fact creates the continuous need for new products, new production lines and new control methodologies. The FleXible PRoduction Experts for reconfigurable aSSembly technology (XPRESS) project [7], a cooperative European

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project involving industry and academia, studied this issue in order to define a new flexible production concept. This concept, based on specialized intelligent process units, called *manufactrons*, was able to integrate a complete process chain, and included support for production configuration, multi-variant production lines and 100% quality monitoring [26]. The concept was demonstrated for the automotive, aeronautics and electrical component industries, but it can be transferred to nearly all production processes.

The latest trends in intelligent manufacturing are related with shop-floor equipment virtualization, fostering the easy access to machine information, allowing collaboration among shop-floor equipment and task execution on demand. The *manufactron* concept was further developed under the project called Intelligent Reconfigurable Machines for Smart Plug&Produce Production (I-RAMP[3]). The goal was to shorten the ramp-up phase time and manage the scheduled and unscheduled maintenance phase time. This goal was achieved by the development of the NETwork-enabled DEVices (NETDEVs), which acted as a technological shell to all the industrial equipment, converting it into an agent-like system and tackling the existing gaps between hardware and software [23]. NETDEVs are intelligent agent-based production devices that are responsible to equip the conventional manufacturing equipment - both complex machines, such as industrial PCs or PLC, and sensors & actuators - with standardized communication skills, along with intelligent functionalities for inter-device negotiation and process optimization. By wrapping equipment components with the NETDEV shell, they become equipped with built-in intelligence. This is at the base of the Smart Component concept [24], which will be further explored in Section 3.

B. *Reconfigurable manufacturing systems*

Reconfigurability has been an issue in computing and robotics for many years. In general, reconfigurability is the ability to repeatedly change and rearrange the components of a system in a cost-effective way. Koren *et al.* [8] define a Reconfigurable Manufacturing Systems (RMS) as being "[..] designed at the outset far rapid change in structure, as well as in hardware and software components, in order to quickly adjust production capacity and functionality [..] in response to sudden changes in market or in regulatory requirements". Merhabi *et al.* [9] complemented this definition with the notion that "reconfiguration allows adding, removing or modifying specific process capabilities, controls, software, or machine structure to adjust production capacity in response to changing market demands or technologies [..] provides customised flexibility [..] so that it can be improved, upgraded and reconfigured, rather than replaced".

RMS are seen as a cost-effective response to market changes, that try to combine the high throughput of dedicated production with the flexibility of flexible manufacturing systems (FMS), and are also able to react to changes quickly and efficiently. For this to be accomplished, the system and its machines have to be adapted for an adjustable structure that enables system scalability in response to market demands and system/machine adaptability to new products. RMS are composed of reconfigurable machines and open architecture reconfigurable control systems to produce a variety of parts with family relationships. The structure of these systems may be adjusted at the system level (e.g., adding/removing machines) and at the machine level (changing machine hardware, control software or parameters).

C. *Industrial applications of agent systems*

Duffie and Piper [10] were one of the first to discuss and introduce a non-hierarchical control approach, using agents to represent physical resources, parts and human operators, and implementing scheduling oriented to the parts. Yet another manufacturing system (YAMS), introduced by Parunak *et al.* [11], applies a contract net technique to a hierarchical model of manufacturing system, including agents to represent the shop floor. The autonomous agents at Rock Island Arsenal (AARIA) [12] control a production system with the goal to fulfil incoming tasks in due time, focusing on the dynamic scheduling, dynamic reconfiguration and in the control of manufacturing systems that fulfil the delivering dates. The manufacturing resources, processes and operations are encapsulated as agents using an autonomous agent approach.

Some relevant approaches have been introduced in this domain. The product resource order staff architecture (PROSA), proposed by Brussel *et al.* [2], is a holonic reference architecture for manufacturing systems, which uses holons to represent products, resources, orders and logical activities. Gonçalves *et al.* [13] presented an approach based on co-operating agents to the reengineering production facilities. The approach focus on several aspects related to enterprise dynamic reconfiguration due to product redesign or changing demand, and on optimizing the production process or removing errors that might have emerged.

In spite of all the research described above, only a few industrial/laboratorial applications were developed and reported in the literature. Bussmann and Schild [14], as part of the *Production 2000+* project, use agent technology to design a flexible and robust production system for large series manufacturing that meet rapidly changing operations in a factory plant of DaimlerChrysler, producing cylinder heads for four-cylinder diesel engines. This agent-oriented collaborative control system, proved to be useful to control widely distributed and heterogeneous devices in environments that are prone to disruptions and where hard real-time constraints are crucial.

Cooperative Engineering concerns the application of Concurrent Engineering techniques to the design and development of products and of their manufacturing systems by a network of companies coming together exclusively for that purpose. Gonçalves *et al.* [15] presented an implementation of a framework for Cooperative Engineering based on a general framework of distributed hybrid systems and MAS. More examples of agent-based approaches in manufacturing systems can be found in [16]-[18].

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III. Adaptive Smart Manufacturing Systems

The goal of XPRESS was to realize an Intelligent Manufacturing System (IMS) and to establish a breakthrough for the factory of the future, with a new flexible assembly and manufacturing concept based on the generic idea of "specialized intelligent process units" (referred to as *manufactrons* in the context of XPRESS) integrated in cross-sectorial learning networks for customized production and flexible system organization. This knowledge-based concept integrates the complete process hierarchy, from the production planning to the assembly, the quality assurance of the produced/assembled products and the reusability of process units. Different functionalities within a factory are encapsulated in specialized intelligent process units called "Smart Components". By doing so, a single Smart Component is able to perform the assigned tasks optimally within linked networks by considering their knowledge. The mechanisms of self-learning, self-organization, knowledge acquisition (experiments), as well as the use of shared communication opportunities, which are required for performing successfully, are stored in every Smart Component.

A. *Industrial Smart Components*

A Smart Component is a self-contained entity, which encapsulates expertise and functionalities, and that interacts with its environment by the exchange of standardized synchronous messages. Being self-contained, it is expected that a typical Smart Component can be included to a smart manufacturing system by just plugging an additional device (into the factory's network). Therefore, the Smart Component has to be realized as an independent component (comprising software and hardware) rather than a distributed set of parts, where a lot of different parts of the component are to be integrated into different systems of the factory – Enterprise Resource Planning (ERP), Manufacturing Execution Systems (MES), or different kinds of Programmable Logic Controller (PLC) systems [19].

The Smart Component shall not only realize a simple functionality, but also provide expertise on this functionality to the outer world. This allows the outer world to state a task to be fulfilled to the Smart Component without the need to know about every small detail associated with the task. The encapsulation of expertise is therefore the solution to demands stated by multi-variant production and flexibility in terms of production resources.

The Smart Component can be seen as an autonomous agent, able to decide the best way to reach its given goals, but not when to do it. The task execution is triggered from outside as defined by a Smart Component from a specific category, named "workflow manager", responsible for overlooking the factory level with dedicated knowledge expertise [20]. This results in a Smart Component hierarchy: "Production Smart Components" (executing basic manufacturing tasks) and "Super Smart Component" (coordinating groups of Production Smart Components); "Workflow managers" (controlling the production flow of an item) conforming the manufacturing execution system up to production planning; "Configuration Smart Components" responsible for finding an optimum production configuration and for the creation of workflow managers for different product variants or for varying production conditions.

B. *Communication*

Communication between different systems is a major challenge in industrial environments. Most communication channels are particularly tailored to different systems and are often proprietary. Hence, integration of equipment requires additional engineering and makes it difficult the simple replacement of systems. On the other hand, if standard connections are used, the process slows down in most cases and finally just covers a subset of the necessary functionalities [19]. A generic understandable task description, describing the production tasks to be performed by a particular machine for a certain class of products can be a solution for this problem. The basic approach of the Smart Component communication scheme is a synchronous exchange of documents. For that, only three types of documents exist: Task Description Documents (TDD); Quality Result Documents (QRD); and Smart Component Self Description (SCSD). This approach led to the development of a uniform and standardized communication protocol for the Smart Component framework.

C. *Smart Component Networks*

The Smart Components are hierarchized into three categories according to their function: Configuration Smart Components responsible for finding an optimum production configuration and for the creation of a workflow manager template that can be instantiated to produce the product variant; Workflow Manager controls the production flow of an item according to the workflow manager template; Production Smart Components responsible for executing basic manufacturing tasks and/or for coordinating groups of production Smart Components.

A major challenge of the approach is the interaction of the different components of the whole system. The communication scheme between components of the different layers (ERP, shop floor and cell level) and also within the layers must be powerful, flexible and extensible. The concept of Smart Component network comprises the Production Configuration System (PCS), the Workflow Execution System (WES), and the lower level Smart Components: Super Smart Component, Production Smart Component and Handling Smart Component.

The PCS is divided in three components: production simulation system (PSS), production execution system (PES), and finally production quality system (PQS). The PSS performs simulation tasks, using different workflows with various production Smart Components and configurations. On the other hand, the PES is responsible for receiving and selecting the best configuration from production jobs issued by external ordering systems, such as SAP, Baan or MES. Regarding PQS, this component is responsible for storing and retrieving the quality results in XML formatted files denominated quality result documents (QRDs), which are generated at the end of the production cycle and contain the complete quality information of the entire production process and the product itself.

The WES, instantiated by the PCS during the simulation phase or production phase, consists of a workflow manager (WFM) and a quality manager (QM). This component, the WES, is the mediator between the PCS and all the other production Smart Components (PMs), handling Smart Components (HMs) or super Smart Components (SMs). Each started instance of WFM or QM is responsible for the control and organization of the Smart Components related to the process. This allows the WES to suspend or to persist the Smart Components, if no activity is to be performed. It is the responsibility of every Smart Component to communicate with lower or higher level Smart Components (SMs or WES "Smart Component"). As far as the communication goes, it is via the exchange of XML data between the components and the system. The system's communication is synchronous, therefore, each TDD sent to a Smart Component must result in a QRD. In case that the operation is not performed, a QRD containing an error message must be sent to the upper level.

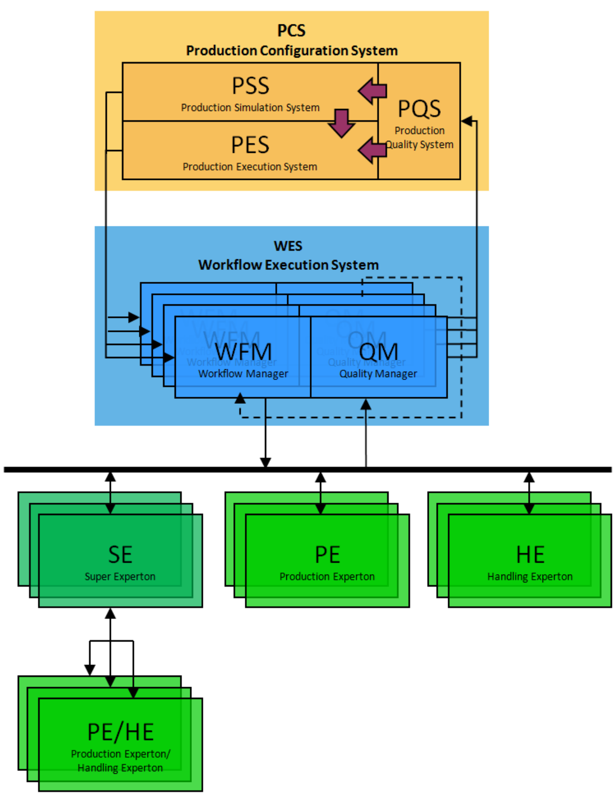

Figure 1 – Smart Component Network

A production system implemented via a Smart Component network, in which several production equipment and therefore Smart Components are considered to execute a process step, the Production Configuration System (PCS) collects the different specifications and generates a TDD. This file can then be understood by all Smart Components that are considered for the process. The structure of MSD and TDD documents is defined in such way that the integration and transformation can take place as easily and unambiguously as possible. An overview of the Smart Component architecture with the communication between layers is given in Figure 1. During production, the Workflow Execution System (WES) sends the TDD to a particular Smart Component (production equipment). Ideally, this happens simultaneously with the loading of the work piece. Due to the fact that it possesses all the necessary information, the Smart Component should now be able to execute the process step successfully. The task description is a high-level document and should not be mistaken for a batch sheet or recipe: in most cases the task description is less extensive but at the same time more flexible than a pure batch sheet specification. At the end of the process step, the product and quality data are returned to the WES simultaneously with the physical unloading of the work piece. The shape of the QRD sent to the WES is also predetermined by the MSD in order to ease the analysis of the resulting quality.

The radical innovations of the "Smart Component Networked Factory" are knowledge and responsibility segregation, trans-sectoral process learning in specialist knowledge networks. The concept is built on coordinated teams of specialized autonomous objects (Smart Components), each knowing how to do a certain process optimally. This architecture allows continuous process improvement, and therefore the system is able to anticipate and to respond to rapidly changing consumer needs, producing high-quality products in adequate quantities while reducing costs.

IV. MULTI-AGENT IMPLEMENTATION OF THE NETFACTORY

As explained in the aforementioned sections, one of the steps forward on the reconfigurability in networked factories is the encapsulation of the equipment with software, extending it with communication capabilities and intelligent functionalities, such as negotiation. This kind of approach will allow not only the inter-equipment communication and collaboration, but also the communication between the shop-floor equipment and any software component, assuming it is also encapsulated with the same technology. This will leverage a much more flexible and effective way of equipment configuration, paving the way for the Network Factory implementation, and therefore, the shop-floor reconfigurability.

This way, a simple MAS was developed to mimic the pertinent behaviours and interactions between the most important Smart Components, and thus, analyse and predict the problems that might occur in a real industrial environment, at a collaborative and cooperative level. As can be seen in Figure 1, there are three different levels of abstraction present in the Smart Component Network, but only the first and the last ones were considered for the MAS modelling. This

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selection lies on the fact that only problems on the shop-floor reconfiguration will be analysed, not considering if the production is running well or not (monitoring and controlling), but instead, take into account the negotiation and collaborative abilities to verify if the requirements for fast shop-floor reconfiguration are met, in the presence of a new product variant.

Therefore, Configuration Smart Component and Production Smart Component Agents were developed, and as explained in Section 3, the first one is responsible to find the optimum production configuration according to some product requirements, and the latter one is intended to execute the basic manufacturing tasks. Hence, in terms of information flow, whenever a Production Smart Component Agent enters into the network, it should be able to generate a MSD, and send it to the already existing Configuration Smart Component Agents, so they can know how the shop-floor can be configured using the available equipment and according to some product requirements. The first step towards the production process is related with the information sent to a certain Configuration Smart Component Agent about the product specifications, and the generation of the corresponding TDD to subsequently send it to the available Production Smart Components Agent with the matching capabilities, for shop-floor operation. Furthermore, when the Production Smart Components Agents finish their operation on the production process, the next step is the generation of the QRD that is then sent to the Configuration Smart Component Agent to update and report the information about the equipment's production performance. This quality feedback will drastically influence the selection of the available Production Smart Components in the optimum production configuration, benefiting the equipment with better performances, tending, this way, to choose the most reliable and effective ones.

As previously mentioned, one of the MAS purposes is to study the problems associated with collaborative activities like the ones described earlier, when the Configuration Smart Component Agent delegates TDDs to Production Smart Component Agents to act accordingly, and subsequent feedback to report the process quality by means of QRD. However, most of the collaborative abilities can lead to a conflict situation, mainly when two different entities are trying to establish a partnership with the same third party. In the context of the Network Factory, this can occur when there are several instances of Configuration Smart Components that can include in their optimum production configuration the same Production Smart Component to operate on the shop-floor level, if this search is made concurrently. One of the techniques associated for conflict resolution is the market-based negotiation. This concept can be simply explained as the increase of a resource cost until only one "costumer" is willing to pay for the achieved price. For the implementation of this technique, *Utility*, *Cost* and *Threshold* functions were built to measure the overall usefulness of using a certain Production Smart Component on the production configuration. The first one measures how distant an equipment operation is from the ideal product specification, the second one returns a value of how much an equipment execution can cost (not its actual running cost, but only a measure representative for this problem) based on QRDs information – as much worse the equipment performance is, the higher is the cost associated to it, and the latter one is how much an agent is willing to pay, based on the utility previously calculated – if the utility is high, the threshold value will also be, and vice-versa. Hence, when the same Production Smart Component Agent is the most suitable one for different Configuration Smart Component Agents, the cost of Production Smart Component Agent's execution will be increase, until only one Configuration Smart Component Agent remains with the threshold value above the cost.

V. Discussion and Future Work

A. Results from the multi-agent implementation

The strategies presented on the previous sections regarding MAS, along with the agent paradigm and well structured communication processes (MSD, TDD and QRD), proved to be an effective and reliable approach, since some of the problems that arise from equipment collaboration were studied and successfully solved using the market-based negotiation approach. The modelled MAS represents a short step forward, but not less important, towards a flexible and extensible production reconfiguration, taking into account the complex industrial dynamics and heterogeneous environments. One of the most important advantages of the MAS characteristics is undoubtedly the decentralized approach that verifies the fault tolerant property, in case of sudden equipment failure. The networked factory will maintain its communication and collaboration activities, avoiding stopping the production process due to component non-dependency issues, minimizing costs and maximizing the network reliability. Another important concept presented in this paper is the task-driven communication, in which equipment execution on shop-floor level are specified in XML-based format, and used to delegate responsibilities for operation according to precise specifications (TDD), and receive a valuable feedback on the equipment quality execution (QRD). Comparing with manual reconfigurability, which in turn reveals to be not cost effective, this concept is an important step forward regarding the automatic reconfiguration of equipment for shop-floor operation.

B. Limitations and future extensions of the approach

The main goal of the work presented in this paper is to provide methods, that can be either fully automated or an aid to the planning engineer, that selects which Smart Components to use for a specific job (new product or variant); this will answer the question: "which is the best configuration for this task?"

From the modules that build the configuration Smart Component, the Production Simulation System (PSS) is the one responsible for the creation of new configurations to answer a specific Job description. The assignment problem is a special type of linear programming problem where resources are being assigned to perform tasks [21]. There is a simple algorithm to efficiently evaluate the solution. This algorithm is known as the Hungarian Method and is able to retrieve the best set of Smart Components for a set of tasks. However, this approach is not helpful in the present context mainly due to the fact that the data made available by the Smart Component (each Smart Component provides a self description document with its typical production capabilities, times and quality levels) does not take into account the impact of working in tandem with other Smart Components. This is the main reason to include a simulation tool on the decision process. To be effective, this tool has to be able to analyse several hundreds of different line configurations. A specific data development analysis model referred to as Charnes, Cooper and Rhodes (CCR) [22] model is a fractional programming technique that evaluates the relative efficiency of homogeneous decision making units, in our case, the relative efficiency of Smart Components. The general efficiency measure, which will be referred as the cross-reference comparison, is presented in (1).

$$\mathrm{E_{ks}} = \frac{\sum_{\mathrm{y}} \mathrm{O_{sy}} \mathrm{v_{ky}}}{\sum_{\mathrm{x}} \mathrm{I_{sx}} \mathrm{u_{kx}}} \quad (1)$$

where: $\boldsymbol{O_{sy}}$ are the output measures $\boldsymbol{y}$ of the Smart Component $\boldsymbol{s}$; $\boldsymbol{v_{ky}}$ are the weights of the "target" Smart Component $\boldsymbol{k}$ to output $\boldsymbol{y}$; $\boldsymbol{I_{sx}}$ are the input measures $\boldsymbol{x}$ of the Smart Component $\boldsymbol{s}$; $\boldsymbol{u_{kx}}$ are the weights of the "target" Smart Component $\boldsymbol{k}$ to input $\boldsymbol{x}$; $\boldsymbol{E_{ks}}$ is the cross- efficiency of Smart Component $\boldsymbol{s}$, using the weights of "target" Smart Component $\boldsymbol{k}$.

An optimal value $\boldsymbol{E^*_{kk}}$ for the cross-reference comparison is obtained by maximizing (2):

$$\mathrm{E^*_{kk}} = \frac{\sum_{\mathrm{k}} \mathrm{O_{ky}} \mathrm{v_{ky}}}{\sum_{\mathrm{k}} \mathrm{I_{kx}} \mathrm{u_{kx}}} \quad (2)$$

subjet to:

$$\mathrm{E_{ks}} = \frac{\sum_{\mathrm{y}} \mathrm{O_{sy}} \mathrm{v_{ky}}}{\sum_{\mathrm{x}} \mathrm{I_{sx}} \mathrm{u_{kx}}} \leq 1 \ \forall\, s$$

$$v_{ky} \geq 0, u_{kx} \geq 0, and \sum_{x} I_{sx} v_{kx} = 1$$

If $\boldsymbol{E^*_{kk}}$ is equal to 1 then there is no other Smart Component which is better than Smart Component $\boldsymbol{k}$ for its optimal weights. Solving this optimization to all the Smart Components, then it is possible to select the ones that are not optimal ($\boldsymbol{E^*_{kk}} < 1$) and remove them from the solution space. The cross reference comparison leads to Pareto optimal solutions but it is not a sufficient condition.

VI. CONCLUSIONS

The Smart Component network concept meets the challenge to integrate intelligence and flexibility at the "highest" level of the production control system, as well as the "lowest" level of the singular machine, and precludes the shift of the production process from a resource-efficiency perspective towards knowledge-based and customer-driven approach. This networked factory approach allows the implementation of a multi-variant system making it possible to have an adequate number of production lines for the manufacturing of adequate quantities of respective goods using an adequate the number of Smart Components in order to meet the requirements of increasing product variants and producing at ever-smaller lot sizes. Due to the knowledge and responsibility segregation within the system, the various production units are easily extendable and exchangeable and thus offer an unlimited "plug & produce" functionality. Different product variants can be produced with the same assembly units (Smart Components) on the same production line. The new Smart Component concept achieves a high level of reusability of assembly equipment and is fast, flexible, reconfigurable, and modular. New developments of this concept, currently being explored include its adaptation to fast ramp-up and equipment re-use scenarios [25].

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