Introduction to Shop-Floor Control

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INTRODUCTION

A shop floor can be defined as all the production and human resources needed to produce semifinished or finished physical goods. A shop floor is usually organized according to the complexity of the product flow and the flexibility of the resources. For instance, for high variety manufacturing, the shop floor may be organized in job shops when product flows are arbitrary and resources are flexible. In contrast, for high volume manufacturing, a shop floor may be organized as a flow shop or an assembly transfer line. The main objective of a shop-floor control (SFC) system is to keep production execution as close as possible to its plan by taking appropriate corrective actions. In order to meet this objective, SFC system need to measure current execution and compare this feedback with the plan to detect any deviations from the plan as illustrated in Fig. 1.

Some of the main attributes of SFC include

- short-time horizons (e.g., minutes) in comparison with planning (e.g., days or weeks);
- the need to compensate for disturbances and modeling errors in the planning system; and
- the need to interface with a myriad of physical equipments and devices to get feedback.

The combination of the above-mentioned attributes makes optimization of SFC a major challenge in terms of architecting SFC systems.

In this article, the classical centralized approaches and modern distributed approaches to SFC are presented. This is followed by an example of modern SFC to illustrate the manner in SFC systems increasingly encompass manufacturing execution system (MES) and supervisory control and data acquisition (SCADA) levels of enterprise architectures. Some recent developments in feedback control approaches for SFC are also presented along with architectural, functional, technological, and human-centric considerations.

THE CLASSICAL VIEW OF A SHOP-FLOOR CONTROL SYSTEM

The classical view of an SFC consists of an SCADA system of which the main functions are production supervision, data acquisition, and estimation of key performance indicators (KPI) and their transmission to upper decision levels. Such SCADA systems are useful to production managers for tracking customer orders and work in progress (WIP). SCADA systems are integrated into an MES to support other functions such as quality control (SPC, statistical process control) and preventive maintenance. Typically, such integration entails data transfer between an SCADA central host computer with a variety of devices including remote terminal units (RTUs), programmable logic controllers (PLCs), and operator terminals [1]. Therefore, in the classical view of SFC, its inputs are at the level of production planning (e.g., from Materials Resource Planning (MRP) level) and outputs are supervision information regarding WIP, inventory level, machine status, and performance. The resulting architecture of such classical SCADA systems is hierarchical and compliant with the federative Computer Integrated Manufacturing (CIM) concept, being monolithic (central-

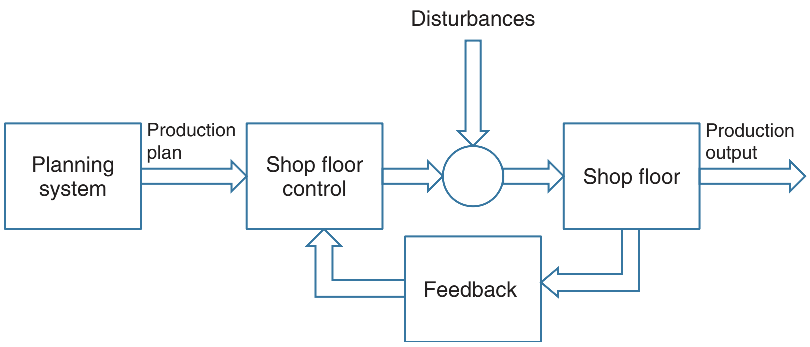

Figure 1. Functioning of shop-floor control.

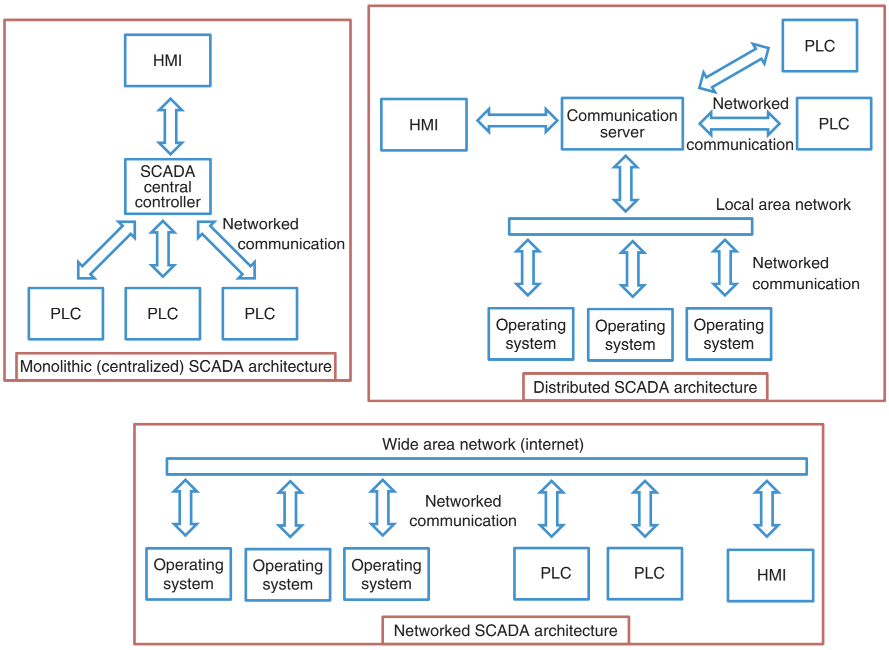

Figure 2. Typical SCADA architectures. *Source*: Adapted from NCS [1].

ized), distributed (using a local area network, LAN), or, more recently, networked (using a wide area network, WAN), as shown in Fig. 2. The latter introduces possible heterarchical relationships among operating systems that will be presented latter in this article.

This classical view of SFC, reducing SFC functions to supervision, low level control, and data acquisition are still considered important in process industries where the continuous and homogeneous aspects of resources, products, and data enable global and visual supervisory human–machine interface (HMI) to be designed for decision-makers. An important aspect of SCADA systems in such industries concerns the safety of controlled processes. Modern SCADA systems are also concerned with network security, especially when they are part of a critical infrastructure such as power generation. A typical classical view of SFC using SCADA can be found in Dieu [2].

Decision-making in classical SFC using SCADA is predominantly manual (e.g., to prevent from human injuries) and automatic control is limited to physical process control (e.g., Proportional Integral Derivative (PID) control through a PLC). When applied to more complex, heterogeneous production environments, such as discrete product manufacturing systems with random disturbances, the lack of automated decision-making in classical SCADA at higher levels of production is a major short coming. This has led to the need to integrate decision-making capabilities in the control loop shown in Fig. 1. For example, Wysk and Smith [3] proposed a formal functional vision of SFC, addressing the scheduling issue using graph theory, modeling SFC as a kind of discrete event systems. Such functions are not traditionally handled in SCADA systems for the process industry, thus motivating the modern view of SFC systems, which is described in the following section.

THE MODERN VIEW OF SHOP-FLOOR CONTROL SYSTEMS

Nowadays, owing to the increase in the complexity of controlled systems, the lack of midterm range production visibility and the increase in the number and potential consequences of disruptions, it has become very desirable for SFC to have decision-making ability in order to adapt to disturbances [4]. Therefore, SFC is a key interface between systems that plan and schedule production and systems that work in real time. This evolution has been partly influenced by the Japanese way of thinking, with the just-in-time philosophy (pull systems). This philosophy implies a closed loop between production and customers; this is in contrast with the classical MRP way of thinking, which pushes products through the resources on the shop floor. Intheory, there is no real need to adapt production in a system like this as all is planned and decisions are made at MRP level; thus, the SFC is only required to supervise production.

This evolution has also been made possible by the technological advances in computing and communication that allow rapid acquisition of shop-floor status and real-time decision-making. Real time in this context means that the computational results are obtained much faster than the rate of change of shop-floor status; the decisions can thus be executed with high fidelity. Therefore, the term *control* in SFC has now evolved to mean that a higher level feedback loop operates between planning/scheduling level and real-time level, updating information, and adapting planned/scheduled production to the real situation on the shop floor. These SFC systems consider constraints that are not usually considered by planning or scheduling production systems, such as the real states of production resources, capacities, tool management, conveyor system, and inventory levels. Therefore, there is an emerging need for corresponding real-time control algorithms that maintain near-optimal performance at all times.

Consequently, modern SFC approaches integrate SCADA systems as a lower level component coupledto higher level decision-making abilities ensuring a more effective and efficient control of production resources. Typically, such high level decision-making abilities in modern SFC concern scheduling decisions, workload management, and capacity planning and tend to overlap with MES and enterprise resource planning (ERP) levels [5]. This means that traditional low level monitoring (SCADA) had to be adapted to consider this evolution. For example, if Kanban systems are used to control production resources, then its SFC system must ensure that appropriate policies are followed (e.g., no more parts than the number of Kanbans).

Figure 3 illustrates the classical hierarchical breakdown of the time horizon in production planning and control. It is inspired from the ISA-95 international standard for the integration of enterprise and control systems and the IEC 62264 international standard for enterprise-control system integration (based on the ISA-95 standard) that introduces a manufacturing operations management model [6]. In this figure, the way SFC has evolved to encompass more high level decision control loops is highlighted, leading to an approximate functional

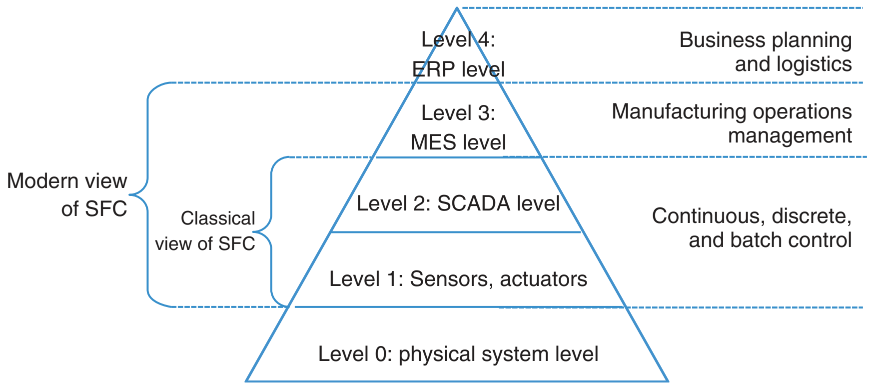

Figure 3. Evolution of SFC. *Source*: Adapted from ISA-95 and IEC-62264.

definition of modern SFC as follows:

$$\text{Modern SFC} = \text{MES} + \text{SCADA}.$$

An important aspect of the modern SFC also concerns the control of resource efficiency. Efficiency is related to the way resources are used to attain production objectives. Efficiency considers, for example, capacity planning; maintenance KPI such as mean time to failure (MTTF), mean time to repair (MTTR), and mean time between failures (MTBF) [7, 8]; and lean/sustainability constraints such as inventory level control and power consumption control. This evolution toward "lean SFC" has been largely motivated by the Toyota way of thinking (Toyota production system, TPS), [9] which gives SFC an important role of maintaining customer satisfaction and internal efficiency. Another illustration concerns the natural integration of kaizen mechanisms within the TPS, aimed to improve KPI through minor but continuous improvement at SFC level. Kaizen decisions are clearly made at SFC level; the local quick response quality control (QRQC) decision mechanism highlights the following aspect: this mechanism basically concerns quality but QRQC decisions impact SFC as operators may modify their own production activity with regard to quality issues. Another feature of modern SFC concerns bottleneck resource management, as proposed by the theory of constraints (TOCs) [10, 11]. According to this approach, the overall effectiveness of a system is essentially guided by its internal constraints and SFC should pay attention to these bottlenecks, controlling them accurately, ensuring that their input stock is never empty, while approximately controlling the others that are guided by the bottleneck (Drum, Buffer, and Rope). Specific scheduling rules should apply in this context and SFC must handle this aspect. Mixing the just-in-time (JIT) philosophy with the TOC and push methods is also considered in modern SFC. For example, the ConWIP method [11, 12] or demand flow technology (DFT) [13] is bridging the gap between these methods and influences the way modern industrial SFC are designed and used. Meanwhile, these industrial SFC tools are often devoted to specific shop-floor systems, such as line assembly systems within a mass customization context. The general assumption is that demand does not vary too much.

In other types of shop floors with more complex production flows (e.g., flexible manufacturing systems), or where demand varies considerably (highly customized production, niche production, etc.), the number of efficient/effective industrial tools is low and the risk is to reduce SFC to "simple" heuristic decision rules at MES level coupled with an SCADA system [7], thus implying a long-term low visibility. For this kind of SFC, research has focused on compensating this limitation because it is impractical to design standardized solutions. Formal process planning schemas for SFC have been proposed by identifying information requirements that are unambiguously expressed as a function of the shop-floor activities required to manufacture a product [14]. This enables any generic SFC system to change its actions to flexibly manufacture different parts or the same part using different resources by appropriately modifying the information in its databases and thereby allowing real-time decision-making in the SFC to determine routing and process plans.

Typically, simulation is used to forecast the behavior of SFC, see, for example, [15], because the increasing integration of various functionalities with different time windows, decision variables, and parameters increase the decisional complexity of SFC [5]. The responsiveness of SFC can sometimes be a disadvantage because of the "nervousness" it can cause, which is a well-established issue in MRP systems. The link between SFC and planning layers was recently investigated for developing automated exception analytics systems to monitor and prioritize shop-floor exceptions systematically based on a postoptimality analysis of plans being executed [16].

Other research approaches based on simulation range from capacity planning in ERP to real-time feedback control to compensate for random perturbations [17]. Treating SFC as a continuous variable control problem in which timing of discrete events is controlled has led to a body of work in which controllers can be highly distributed for real-time scheduling [18–20]. This continuous variable SFC approach lends itself to real-time decision-making for routing and process parameters [20, 21]. The resulting dynamics can be analyzed using control theoretic techniques and have been proved to be globally stable for general shop-floor configurations including job-shop-like configurations with dissimilar machines with alternate routings without any restrictive assumptions [22].

AN ILLUSTRATIVE EXAMPLE OF A MODERN SFC SYSTEM

The AIP-Primeca FMS cell is a shop floor located at the University of Valenciennes and Hainaut-Cambrésis (France). This cell was built with the following industrial components:

- A monorail conveyor system with 15 single-direction shuttles [RFID (radio-frequency identification) tagged] and 11 transfer block (TBs) permitting flexible routing inside the cell.
- Seven robotized workstations (WSs) located at specific points on the monorail, which perform automated operations (loading/unloading, assembly, and quality inspection) on the product being manufactured. Loading/unloading consists in loading/unloading a plate on a shuttle, the plate being the support on which the products are made.

Thus, each product is placed on a dedicated shuttle and the set moves from WS to WS. Figure 4 provides an overview of the WSs, their locations, and the conveyor system.

The corresponding SFC architecture, shown in Fig. 5, is based on the "distributed SCADA architecture" shown in Fig. 2 and is augmented with functionalities at MES level. It is composed of the following four levels:

- Levels 0 and 1 are built with mechanical operating systems (Stäubli and Kuka robots; Cognex vision inspection; Montratec monorails, transfer gates, and positioning units), PLCs (750-841 Wago controllers programmed with Codesys), stop and go shuttle devices, RFID R/W (Schneider OsiSense XG), and Ethernet switched automation network.
- Level 2 consists in an OPC server (Schneider OFS), several supervisory stations (equipped with Arcinfo PcVue32), a log server (SQL database server), and an Ethernet area operation information network.
- Level 3 is essentially composed of an MES system including scheduling ability optimization (IBM ILOG CPLEX Optimization Studio).

Typically, the problems to be solved by the SFC system in this cell include:

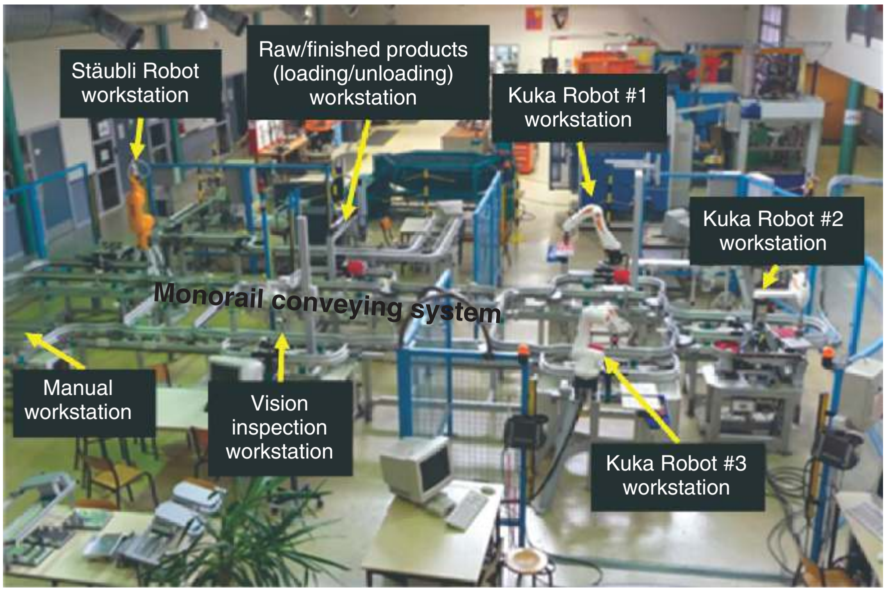

Figure 4. Overview of the AIP cell.

- the scheduling of a limited amount of resources (WSs, shuttles, inventory, and tools) within the time given to make a dynamic set of products;
- the dynamic routing of shuttles containing the WIP;
- the real-time control of WS and transfer gates.

Using this SFC architecture:

- Levels 0 and 1 manage the shuttle routing and WS states in real time.
- Level 2 supervises and monitors the WIP and interfaces levels 1 and 3.
- Level 3 defines the operations to be carried out by WS at levels 0 and 1.

More details about the SFC used in this research can be found in Berger *et al.* [23].

CURRENT RESEARCH IN SHOP-FLOOR CONTROL SYSTEMS

The modern view of an SFC can be seen as a first step toward increased local decision-making capability where events occur and reactivity is needed. There are several major challenges froma scientific and practical perspective. Some are provided in this section and organized according to architectural, functional, and technological considerations.

Architectural Considerations

Classical hierarchical architectures are rapidly evolving toward more distributed/heterarchical SFC architectures, typically by extending the SCADA architecture. The basic idea is to integrate redundancy in the control decision abilities and horizontal cooperation mechanisms in thecontrol decision process among decisional active or intelligent entities, that is, resources, products, inventories, tools, and so on. The aim is to limit the risks of local controller loss (robustness to failure and ease of restarting) and to enable more "plug and control" approaches making the whole SCADA system more capable of self-reconfiguring as well as self-adapting to changes in the environment and in the production system [24]. This also implies focusing on work at MES level to fine-tune this integration [25].

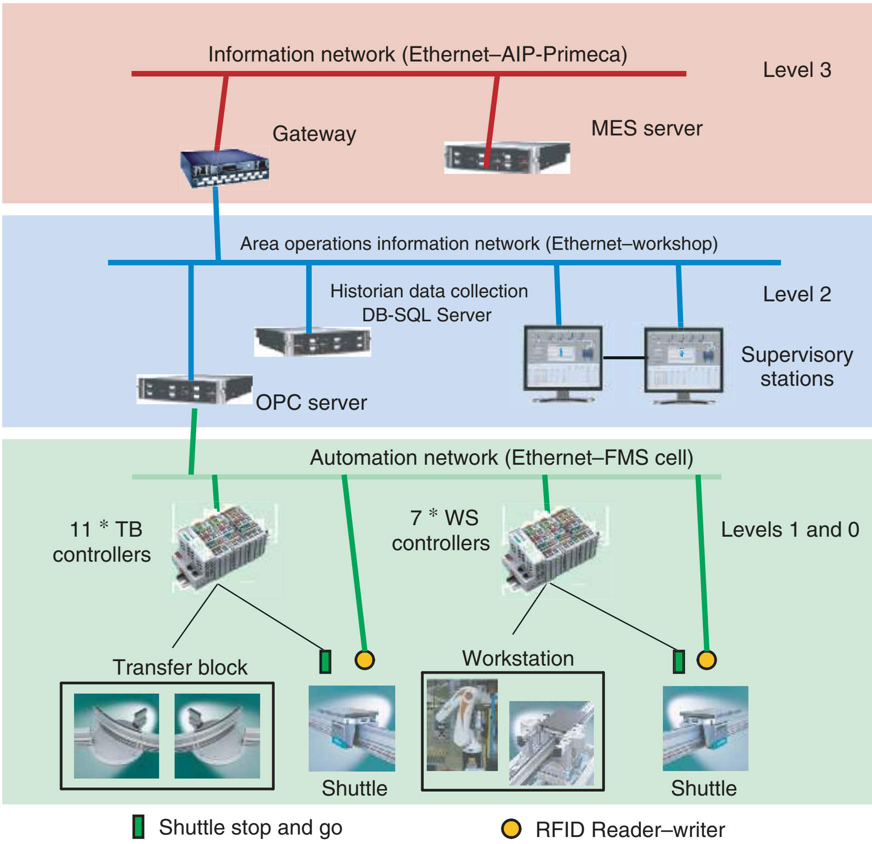

Figure 5. Modern SFC architecture of the AIP cell.

Functional Considerations

The idea is to integrate more functional abilities in SFC to encompass broader time horizons and increased data space for better decisions. This could lead to the integrated cohesive optimization of maintenance, production, and inventory, which are otherwise treated in isolation. The study of robustness is also important nowadays, typically in reactive production scheduling [26]. This issue is increasingly addressed from an operation research point of view. The coupling of optimization and simulation tools in the global context of digital enterprise also seems promising [27, 28].

Integrating intelligence and activeness into entities composing an SFC system (products, resources, inventories, tools, etc.) seems to be another promising research area [29]. From an information management point of view, it would help improve tracking the history of events and use of resources [30]. From an energy management point of view, it would help integrate opportunistic energy gains and improve management of energy costs given the increasing lack of visibility in terms of energy supply (variability of renewable energy power and variability in grid energy costs) [31].

Technological Considerations

Service orientation technology and service-oriented architectures (SOA) is key in the evolution of SFC [32]. Indeed, it enables a "components off the shelves" approach to be used that is required when designing plug and control SFC enabling "plug and produce" production systems [33].

As an illustrative example, the EU FP7 project IMC-AESOP (www.imc-aesop.eu) aims at defining the next generation of SFC systems based on SOA and recent internet technology such as cloud computing and the internet of thingsInternet of Things (IoT) [34].

The IoT and ambient intelligence are also technological solutions enabling the improvement of emerging SFC systems and architectures. This evolution will contribute to design more self-adapting, self-organized SFC [35].

Toward More Human-Centered SFC

Human operators know information the SFC system does not know. Typically, such information comes from outside the SFC system itself, and by interaction with the SFC system, operators could help constrain or bound automated decisions according to this knowledge, thus anticipating events. For example, an important incoming order not yet integrated in the production planning, an operator that suspects a production machine will operate defectively (e.g., furtive error), or a possible incoming supplier strike can be considered through such interaction. In addition, despite all the theoretical developments in learning systems, the human operator is still more able of learning, adapting, and reasoning than computerized systems. Human operators can identify repetitive patterns in production, for example, and can use them to anticipate events or to optimize production over broader time windows.

Consequently, keeping operators in the SFC decisional loops shown in Fig. 1 is still relevant. All the research in these different areas (architectural, functional, and technological considerations) could lead to more human-centered and cognitive SFC systems [36] as the knowledge of human operators shall be merged more easily with the knowledge constructed by various active/intelligent interacting entities rather than in purely centralized SFC approaches. The technology currently available enables this smart integration. Now, time has come for researchers to reintegrate human operators in the loop; fully automated shop floors with nobody inside are no longer considered. However, the interaction of emerging SFC systems with human operators is still poorly addressed by researchers.

Acknowledgment

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