Integration Aspects in Automation – a Technology Survey

Thilo Sauter
Austrian Academy of Sciences
Research Unit for Integrated Sensor Systems
Viktor Kaplan Str. 2, A-2700 Wiener Neustadt
Thilo.sauter@oeaw.ac.at

Abstract

"Integration", in particular vertical integration, has become one of the dominating buzzwords in the automation business. While marketing campaigns mostly in the context of Industrial Ethernet and modular Manufacturing Execution Systems evoke the impression that integration in automation is a new and revolutionary concept, the opposite is true: Integration has always been the ultimate goal of automation. This article presents the historical roots and their evolution up to the present day. Furthermore, it proposes a model describing the three essential aspects of integration, namely, horizontal, vertical, and temporal, and gives an overview of the current technological building blocks such as networks, middleware, and application concepts. Open problems and future challenges in the area are discussed as well.

1. Introduction

The past two decades have brought tremendous advances in network technology, both in the office world and in all fields of automation. Two obvious indicators for this are on the one hand the stunning success of the Internet, whose technological principles have also been widely adopted in small-size local area networks. On the other hand, the lengthy and fierce struggle for an acceptable compromise in fieldbus standardization shows that the automation domain is seen as an important market by the big players. Consequently, as networking in both worlds has reached a mature point, the recent years have seen many attempts to bring the two sides together and to achieve something that had remained wishful thinking for a long time: the idea of *horizontal* and in particular *vertical integration*.

The two terms frequently appear in marketing papers of automation vendors and are not properly defined. Still the basic concept is intuitive: What is meant is a seamless integration of information across all levels of an enterprise, an inclusion of data from the shop floor into a high-level IT context [1], and direct access from the management level down to the process control. This expectance is also reflected in the names major vendors give their turn-key solution frameworks [2]. Denominations like "Industrial IT" or "Totally Integrated Automation" convey the idea of unlimited possibilities.

The essence of integration in the original economics sense is the flow of information and the control of business processes [3, 4]. In automation, the integration concept circles around the same questions, but in a wider scope. Business processes need to be addressed as well as manufacturing processes, and still this is only a subset of an even more comprehensive field today called Enterprise Integration [5].

The purpose of this paper is to give an overview of the communication and information technology issues of integration, in particular manufacturing automation. Even this small part of the whole picture is a wide area with many different yet interwoven aspects that are rarely treated in a systematic way. The root of the problem is that neither the technological basis of integration nor the application concepts evolved in a linear way. Actually, most work was done in parallel, and many solutions were developed independently.

The paper is divided therefore in two major parts. It will start with a brief survey of how the application needs – mainly CIM and its successors – and the associated communication networks in automation evolved. Section 3 presents an approach to structure various aspects of communication and information technology integration in automation. A conclusion finally rounds off the paper and gives an outlook on open issues.

2. Historical background

As mentioned before, what is currently celebrated by major automation vendors as entirely new concept is not all that new. A new aspect may be that today modular solutions are available which can be employed also by small and medium-sized enterprises and which are no longer – for complexity reasons – restricted to big companies. The basic ideas, however, as well as the roots of the current implementations, are much older.

2.1. CIM and the early years

The use of computers in manufacturing started nearly half a century ago, and its evolution goes hand in hand

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with the computing capabilities offered by the available technology. At that time, its application was limited to high-level functions in the field of production planning and preparation. MRP (Materials Requirement Planning) emerged in the 1950s [6] or 1960s [7]. In the 1970s, it evolved into MRP II by integrating increasingly complex functionality like sales planning, capacity management, and scheduling. Apart from the planning level, CAD (Computer-Aided Design) and CAM (Computer-Aided Manufacturing) were well known and closely linked together.

The idea of CIM (Computer Integrated Manufacturing) was finally to integrate the various islands of automation [8]. In this respect, CIM can be seen as the last step in a long evolution of manufacturing technologies and philosophies [9]. The most essential ingredient in CIM was and still is information, and the key to its implementation was the establishment of a transparent information flow inside an enterprise. To cope with the anticipated complexity, a strict subdivision of the information processing into a hierarchical model was devised that became known as the automation pyramid. The model exists in various versions with different naming conventions and numbers of levels, but it typically comprises four to six levels [10] as depicted in Fig. 1.

Along with the definitions of functionalities – which of course varied according to the respective application domain – networks were associated to the individual levels. With regards to the information flow needed for factory and process automation, the approach put forward was to create a transparent, multi-level network [11]. Fig. 1 also shows the various network types used today for these purposes. By the time the term CIM was coined, however, these networks were to a large extent not yet available. The development of MAP, TOP, and finally also the evolution of fieldbus systems are closely related to the attempts to bring the CIM idea to life [12].

It was not before the 1980s that industry and academia actually entered the CIM era [9]. What made application difficult was the fact that CIM was a comprehensive vision and not a solution. Much work was therefore devoted to the development of models structuring the problem of enterprise integration, the automation pyramid being just one aspect. Other approaches focused not so much on communication, but on the decision making and planning process [9,13].

Following the modelling efforts, various pieces of the mosaic were actually implemented: networks, interfaces, databases, and various tools for the CAx topics (computer aided engineering, design, manufacturing, quality, planning). In manufacturing control, a two-level hierarchy evolved in practice, comprising MRP on the higher level, responsible for scheduling, and MES (Manufacturing Execution System) on the lower level, concerned with dispatching [14].

In the early 1990s, the comprehension prevailed that the mostly technical or "mechanistic" view to CIM in the early years of implementation efforts was too narrow [13]. It became apparent that also economic, social and human aspects had to be taken into account [9] and that CIM ultimately has to affect the entire structure and organization of a company. This made implementation overly difficult, and the great expectations were finally not met. As a result of the hype together with reports on implementation failures, the term CIM finally fell in disgrace – at least in Europe – and has a negative connotation up to the present day.

2.2. ERP and MES

During the last decade, the CIM idea evolved further. ERP (Enterprise Resource Planning) derived its name from MRP II and is commonly seen as logical successor of CIM, even though a direct line of descent is by no means evident. Unlike CIM, ERP is driven by products [6]. This evolution was made possible by the progress in information technology, which led to a convergence and integration of not only the manufacturing-specific tools, but also engineering and financial systems up to the interfacing with external customers and suppliers, the ERP system being the "hub" of the entire information system [19]. While MRP II systems were usually tailored to particular market sectors, ERP systems are comprehensive frameworks aiming for total integration of all business processes and functions including procurement, material management, production, logistics, maintenance, sales, distribution, financial accounting, asset

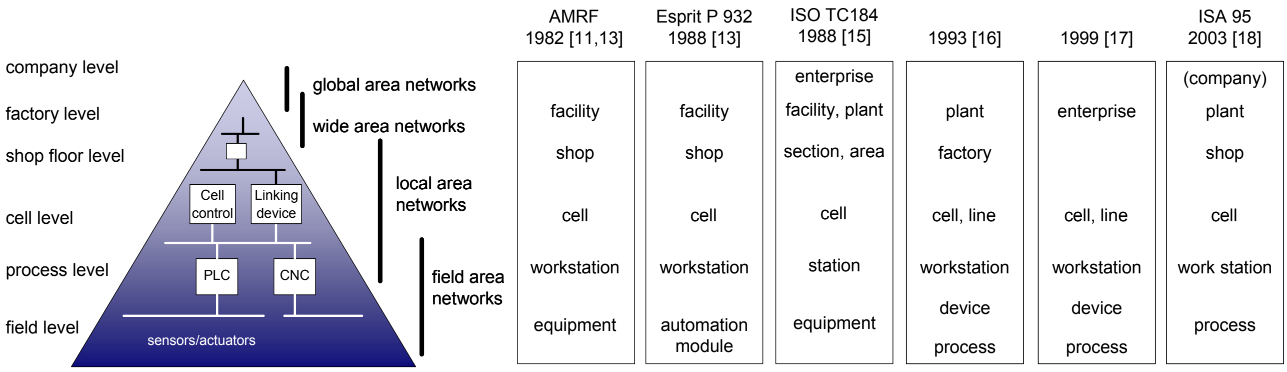

Fig. 1: Various models for automation hierarchies.

management, cash management, controlling, strategic planning, and quality management. As the software is usually modular, it can be configured for any application field, which is nonetheless often a lengthy and highly customer-specific task [20,21].

Below the ERP, which is concerned with rather long-term planning, MESs accomplish the task of short-term planning and create the bridge between office and shop floor. In contrast to ERP systems, whose functions are not clearly defined and depend very much on the product and a given application, MESA (Manufacturing Execution Systems Association) has identified 11 distinct functional areas that cover the basic information needed to run any type of plant [22]. Fig. 2 shows the position of MES, ERP, and related systems within the plant hierarchy. It must be noted, though, that the boundaries are not sharp. Usually there is some overlap, with varying degree depending on industry and application. Likewise, not all MES functions are relevant for a given application, and not all functions need to be provided by a single MES tool, even though comprehensive (but still modular) solutions are available. A typical example is SCADA, for which numerous standalone tools are on the market, but which is can also be embedded in an MES. The three-level hierarchy depicted in Fig. 2 consisting of ERP, MES, and control level is also the typical situation found today from an application point of view, no matter if the plant models comprise more levels (as in Fig. 1).

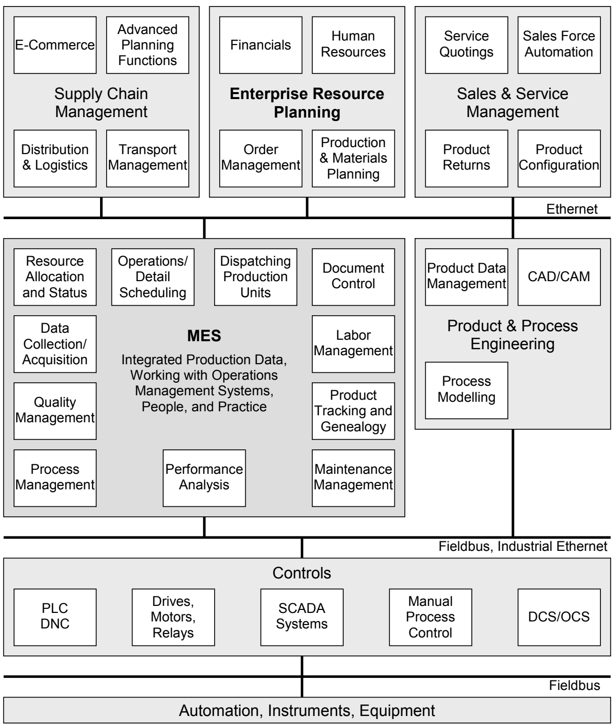

Fig. 2: Plant information model according to MESA [22]

As far as the actual *integration* of the levels is concerned, the real-world situation is a bit different. It appears that ERP and MES are reasonably integrated today [1]. Much work in this area is still in research status, but there are industrial solutions available, even if they do not yet cover the full range of possibilities. By contrast, there is a big dividing line between the MES and control level. In other words, the connection between the process control devices and the MES is lacking, if an MES is deployed at all. Even in the semiconductor manufacturing area, which traditionally exhibits a high degree of automation, the data transfer between process control and the MES is largely done manually [23]. This gap is not surprising. In fact the two areas on either side evolved separately and mirror two different worlds inside a company:

- The users as well as the developers of business-oriented applications like ERP or SCM share an economics background and are focused on a strategic view of the company. MES is usually also attributed to this level, although it belongs in fact to both worlds.
- Production-oriented applications like SCADA, production control, or assembly belong to the operational world. Again, they are mostly well integrated, but the background of users and developers is typically engineering, which stipulates an entirely different view on the overall system.
- Communication requirements inside the two areas are largely coherent: large amounts of data with very relaxed timing requirements on the company level, small chunks of data mostly with real-time constraints on the other level.
- The application context inside the two areas is different: strategic on the upper level, operational on the lower.
- The equipment needed is different and evolved differently. Centralized mainframe computers were and still are typical for the upper level, the lower level requires distributed computing.

Fig. 2 demonstrates that these two worlds are also separated by different networking concepts. In the business context, LANs are predominant whereas the control level is home of the fieldbus. Again this is not surprising because one of the major design guidelines for fieldbus systems was the recognition that in a (real-time) process control context, completely different networking characteristics are required than in the (strategic) office world. Hence, the gap to bridge today not only concerns the linking of two different network types, but also the interconnection of two different mind-sets.

3. The three major aspects of integration

Integration in automation has many facets, and one of the lessons learnt from CIM was that one single model can never cover all aspects. In this paper, we are primarily interested in the communication and information technology side of enterprise integration and the interdependencies of the individual ingredients. We therefore cling to a simple onion-like model (Fig. 3) identifying the three main aspects of modern integration in automation, namely,

- horizontal integration inside the individual levels of the automation hierarchy,
- vertical integration between the levels of the hierarchy, and
- temporal integration (or longitudinal, as termed in [24]) along the life cycle of the system or plant.

This model is not a structure-oriented one like the classical automation pyramid, which introduced a hierarchical decomposition of automation functions. Rather it is a architecture-oriented approach compiling technological building blocks which in their entirety are prerequisites for integration. From the information technology viewpoint, each of the three main aspects is therefore further composed of two sub-aspects,

- communication-related, which refers mostly to the various networks forming the foundation of information transfer and data provision, and
- application-related, meaning that and how the information provided is actually processed.

The communication technology and the application are glued together by a shell of middleware, a term which is used here in a broader sense than usually in software engineering. It denotes a set of developments – middleware concepts in the original sense, description languages, or modelling approaches – which allow for interoperability, portability, or vendor independence. As a matter of fact, this layer of software "technologies" is a (if not the) key enabler for all kinds of integration. Furthermore, it cannot be clearly attributed to a single aspect of integration; it rather affects all at a time, establishing also an interconnection and interrelation between them.

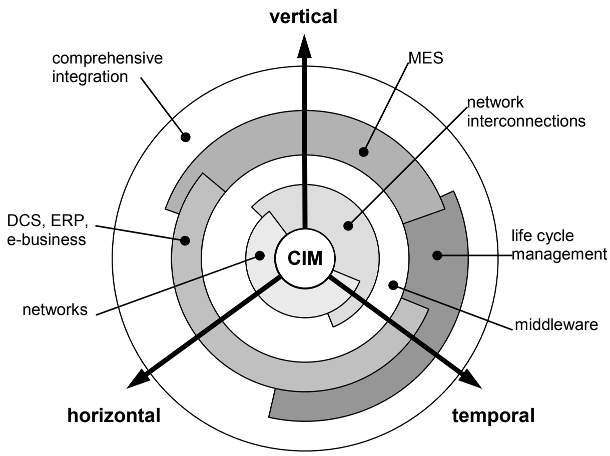

Fig. 3: Model for communication and information technology integration in automation.

The various integration aspects in the model are not independent of one another in practical use, nor were they developed independently. Actually, they build on each other, they partially overlap, and they evolved in a bottom-up fashion. Thus the three axes in the model also have a coarse notion of time attached to them. The starting point was the CIM idea; therefore it is placed in the center. As this vision was too comprehensive to be implemented in a straightforward manner, massive parallel work started to lay the technological foundations. Networks were the first problems to be tackled, middleware was necessary on top of it or became an essential input from outside, and on this basis application integration could only be started. The ultimate goal, where all parallel branches will reunite, is something we could call comprehensive integration, which is the outer shell in the model. In fact this closes the loop back to the original idea reached by means of contemporary approaches.

The automation pyramid cannot be directly mapped to the model of Fig. 3; the individual levels were combined and hidden in the functional elements of horizontal and vertical integration: the networks, their interconnections, and the application-level modules like ERP, MES, and DCS (distributed control systems). Nevertheless, for the detailed discussion in the sequel, the hierarchical structure will again be accounted for, but the pyramid is reduced to the two different worlds reflecting and dominating the status of contemporary automation as discussed in the previous section: the company level and the field level.

3.1. Horizontal integration

The horizontal aspects of integration are restricted to the individual hierarchy levels, thus every level must be treated separately.

The communication technology foundations of horizontal integration are essentially the networks devised for the various levels. On the company level, local area networks have been in use for a long time, and with the evolution of the Internet and TCP/IP also a de facto standard was introduced for the protocol. Although there is still substantial work being devoted to improvements on the lower communication layers (like speed enhancements for Ethernet and wireless alternatives), the overall situation is stable and settled.

On the field level, the situation is still more dynamic. After two decades of development, fieldbus systems have reached a mature status and have found broad acceptance [12,25]. In recent years, much work has been invested in fieldbus extensions that include wireless segments and mobile nodes [26]. Projects like R-Fieldbus demonstrated that an integration of wireless communication channels in traditional fieldbus systems is possible without sacrificing real-time capabilities, albeit with substantial effort [27]. With such hybrid approaches combining heterogeneous network types, a broad and comprehensive coverage of the field level has been achieved. Not many changes are thus to be expected in the near future, the introduction of Industrial Ethernet being a notable exception [28,29].

As said before, middleware concepts are the ubiquitous glue between communication and application, and also between applications themselves. In the office domain, many solutions emerged in the course of time greatly facilitating horizontal integration of applications. Most relevant are CORBA [30] together with its real-time extensions [31], DCOM, Java as portable programming language especially for web applications, and the component-based and object-oriented programming paradigms. Being tailored to office applications, the focus of these classical middleware solutions is on databases and software agents as supported basic resources, and they are less adequate for the special requirements of process monitoring and control [32]. Nevertheless, they are widely used also for automation tasks. The latest trend is to use Web Services as actual middleware which are often considered superior to CORBA and DCOM because of their easier deployment and platform-independence. On top of web services, which effectively specify interfaces, workflows describe processes and are mapped to available web services. Although providing a flexible architecture, this approach leads ultimately to still static relationships. Recent considerations aim at introducing semantic information about the processes by means of ontologies, a concept borrowed from artificial intelligence [33]. This abstract intermediate layer is expected to ultimately provide a kind of look-up feature which in turn will facilitate automatic (re-)configuration of application processes and infrastructure within a plant.

For the fieldbus systems, the great step towards practicable horizontal integration was the definition of profiles and companion standards – more generally the user layer enabling interoperability between devices from different vendors. Equally important and building on the profile concept was the development of device description languages [34,35]. Originally, they were tailored to individual fieldbus systems (e.g., HART DDL, PROFIBUS GSD, CANopen EDS, FF DDL) and laid the foundation for user-friendly configuration and engineering tools. In recent years, XML was adopted as basis for a unification and finally international standardization of device description languages [36].

As far as application aspects of horizontal integration are concerned, not too much can be reported for the field level. Truly distributed applications would be an obvious manifestation of integration and were always one essential argument for the development of field-level networks. Yet, they are still not very common, not to speak of distributable systems, which would allow for much more dynamic deployment [37]. Instead, centralized solutions dominate in industrial practice, certainly also because of the dominant role of PLCs in control applications. Nevertheless, the growing importance of more intelligent field devices and embedded systems, as well as the interest in, e.g., network-based control systems [38] show that this might change in the near future.

On the office application level, horizontal integration is essentially concerned with the current tendency to combine and integrate function-oriented systems to improve the efficiency of business processes. In practice, this involves several technological aspects [39], among which the integration of data is the most obvious. This need not be achieved by the deployment of one single, comprehensive database for the entire enterprise (as in the CIM idea), but requires at least the provision of appropriate gateways between dedicated databases ensuring data transfer, transformation, and above all consistency. Other technological aspects are the integration of applications or components through frameworks for reusability, and finally business processes themselves. An essential enabler for all integration approaches is the current trend towards componentization of software, which allows splitting comprehensive systems into smaller, service-oriented parts. These parts can then be combined according to the actual needs of the customer.

In practice, the integration of business applications today is to a large extent covered by ERP systems [40]. Nevertheless, and despite the modular structure of many ERP solutions, they hardly can satisfy all requirements of a particular enterprise. Thus, and also for economical reasons, it is common to find environments where new ERP applications support only a part of a process chain, while the remaining aspects are covered by legacy systems serving other requirements. The integration of such legacy systems is a major difficulty in integration projects. Although many ERP packages provide standard interfaces or connectors, they are still usually built as monolithic solutions, which makes integration of older systems challenging [39].

Apart from the intra-organizational aspect of horizontal integration, which is in many cases not even recognisable as such, there is another aspect which is closer to the definition of horizontal integration known from the economics literature: the interaction of independent companies in form of networked enterprises [5]. In order to optimize, e.g., supply-chain logistics, it is increasingly common to interconnect respective business systems (like ERP or SCM) between supplier and customer, often across the Internet. Even more than in intra-organizational integration, matching interfaces and data in such inter-organizational integration projects is a problem. Standards like EDI (Electronic Data Interchange) or STEP (Standard for the Exchange of Product Model Data) have been in use for several years, but are facing limitations with the complexity of toady's systems. XML is an emerging replacement also in this area, but actual implementations are still lagging behind, and non-automatic data exchange is still the rule [39]. Extreme, but not undisputed implementations are fully web-based portals. Such solutions have been put forward mostly in the context of e-business to allow even easier interfacing with customers and remote offices [41].

3.2. Vertical integration

The communication technology aspects of vertical integration are simply the interconnection or integration of the different networks used inside an automation system. Today this essentially boils down to the linking of traditional control networks – like fieldbusses – and IP-based networks using various architectural approaches, including protocol conversion via gateways or the use of encapsulation strategies [42]. A hybrid between horizontal and vertical integration is to be seen in the interconnection of remote network segments via a higher-level, mostly IP-based backbone network.

In terms of middleware, the solutions listed in the context of horizontal integration play an important role also here, even though they tend to introduce performance penalties [43]. XML is an emerging and partly already well-adopted standard for data exchange between the automation levels [44]. One technology which deserves special attention is OPC (OLE for Process Control), which is currently the most widely used solution for data exchange between the field level and higher-level applications, e.g., SCADA systems. Also inside the field level, OPC as interoperable data exchange middleware is a de-facto standard. A recent study [45] shows that native COM/DCOM is the most popular data exchange platform for MES, followed by OPC. There are also MES/ERP integration solutions based on OPC. By contrast, CORBA is rarely used for MES. Finally, the current trend to use web services facilitates also vertical integration of business processes on different levels.

From the application viewpoint, the goal of vertical integration is still the old CIM ideal, that is, the integration of systems implemented on different levels in the automation and business hierarchy of an enterprise. On the office level, at least in an intra-organizational context, it is no longer possible to easily discern a hierarchy of applications, the most important reason certainly being that communication and operating platforms are unified. Again, ERP and similar tools have already achieved the integration. One exception might be enterprise-wide data warehouses that are still located on top of the ERP level [39]. On the field level, vertical integration has been fully achieved through SCADA systems which together with the underlying communication technology allow for a transparent data flow. What is left, therefore, is to bridge the gap between production and office environments, that is, to allow for bidirectional online access to shop floor data and their representation in a form suitable for applications on the company level. As stated in section 2, this missing link is to be seen in the MES [23].

3.3. Temporal integration

While horizontal and vertical aspects of integration are widely known and discussed, the temporal aspect is often disregarded. In fact, it is often mixed with the others and thus not treated as a self-contained topic. The temporal (or longitudinal) facet of integration has to do with the changes an automation system undergoes during its life cycle. Most discussions about integration are limited to the actual operation of a plant. There are, however, many more phases of the life cycle which also need to be addressed. Even though the problem of life cycle management was a part of the original CIM concept, the current situation in practice is that for every phase (such as design, engineering, implementation, commissioning, operation, and maintenance) different tools exist which are mutually incompatible. This situation is not surprising, as the individual phases are typically in the hands of different people who need not cooperate (developer, system integrator, or operator). Therefore, comprehensive tools would not be economical from the viewpoint of one individual phase. However, the data describing the system need to be transferred from on phase to the next and need to be kept consistent within the tools. Today, this is often a problem and requires substantial manual interaction [46,47].

The temporal aspects of integration are nearly exclusively found on the application level. Neither communication technology nor the middleware have such aspects. The only exceptions that might be considered are advanced plug-and-play concepts known from spontaneous networking [48] which facilitate the (re-)configuration of an automation system during commissioning and operation. By permitting subsequent installation, removal, or exchange of devices, such concepts also add a temporal dimension. In essence, however, the problem is not the "how", but the "what" of data handling. Key technological aspects are once more XML and databases. What is needed are comprehensive data models, but this is not so much of a technological problem than a semantic and organizational one. On the application side, finally, it is up to the engineering, commissioning, and maintenance tools to use such a comprehensive database.

The details of temporal integration are manifold. Asset management is one topic which becomes increasingly important on the overall enterprise level, but needs to include also field-level device data [49]. The engineering of the actual fieldbus installation is facilitated by concepts like the FDT (Field Device Tool). This widely adopted approach extends and complements the capabilities of device description languages [35,50] by embedding device and profile information in a tool suite accompanying the life cycle of an installation. It is not restricted to the engineering phase, but is applicable also during operation. If such engineering support tools are used during the operation phase of a plant, real-time aspects may become important and must be taken into account [51]. There are, however, attempts to eliminate the need for additional tools (including the software maintenance problems and the need for additional user skills) completely. The method of choice in this case is to implement a web portal as interface. Typical for all approaches is that they start from a comprehensive, consistent description of the devices and their parameters and filter this database depending on the life cycle phase. The user therefore gets access only to a specific subset (or view) coinciding with his role in the life cycle [49].

4. Future challenges for integration

Integration in automation has come a long way since its first inception in the CIM era. Contrary to the initial situation, all basic elements needed are finally available from a technology point of view. What is required today is to put them together in a reasonable way.

This article tried to shed light on some aspects, by far not all of them. An important recognition is that the recent technological developments not only stimulated or revived the old idea, they even accelerated and tightened the integration. As a matter of fact the large-scale introduction of Internet technologies caused the multi-level automation pyramid to crumble down to effectively at maximum three levels. The company level is the strategic one; any further subdivision is no longer applicable, not even in large globalized enterprises. The Internet has already provided the means to fully integrate remote branches in one single corporate network with one common management or planning framework. From the many operational levels only two remain: the actual field level with the process control devices and an intermediate level typically used for controlling purposes.

From the networking point of view, there are in fact already only two levels left today. In the office world and the upper automation level, IP-based networks and Ethernet dominate. Even if fieldbus systems still have their share on the cell level, they are bound to vanish within the next few years. It is the field level that will still belong to them, maybe with some additional specialized and low-level local sensor/actuator systems integrated via controllers acting as simple gateways. Nevertheless, the recent emergence of real-time Ethernet extensions already sparked new competition in the field. In the long run, Real-time Industrial Ethernet will offer a tempting alternative to the classical fieldbus systems and will most probably make some of them obsolete.

But also from the application point of view, there is a trend towards a further reduction of the hierarchy. In plant automation, which was traditionally strictly centralized in the upper two levels (Fig. 4), modular concepts are becoming popular. The overall goal is to enhance flexibility of planning systems and allow for solutions tailored to the needs of the customer. This makes enterprise resource planning and especially manufacturing execution tools attractive also for smaller companies that so far could not benefit from fully-fledged solutions.

Still one step further is taken by approaches to decentralize essential parts of the planning and control functionality by agent-based automation concepts [1,52], aimed at practically dissolving the rigid middle layer of the pyramid, implementing its functionality in software agents attached to the outer levels of the hierarchy. This tendency is supported by complementary trends in the control and enterprise field: On the one hand, control devices will in the long run be indistinguishable from standard PCs as far as computing resources are concerned, and they will exclusively have IP-based connections. Thus they will be able to run more complex planning tasks. On the other hand, ERP frameworks will become even more comprehensive and include functional modules currently belonging to the MES level. Such a mostly distributed approach for the MES level will however impose more demanding requirements on the middleware to support better flexibility. Concepts emerging in the IT world like ontologies to formally describe semantic information will have to be used, and additional abstraction levels must be introduced.

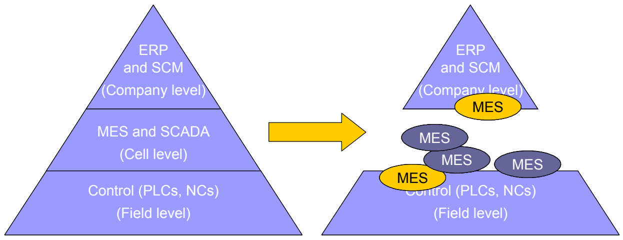

Fig. 4: Application view of the future automation pyramid.

The need for abstract interoperability layers is visible already today. What distinguishes significantly today's situation from the one at the beginning of the CIM era is the availability of a multitude of effective and powerful technological building blocks: widely used protocol standards, middleware concepts, distributed application paradigms, databases, and last not least high-performance computers. All this had not been available three decades ago, when the idea of comprehensive integration in automation was conceived. But, the main problem has not much changed over the years: to find proper interfaces between lots of applications that are to a large extent still not interoperable. From a pure communication technology point of view, OPC and web services seem to have the pole position in the race for highest user acceptance and broadest industry support. In particular web services as abstract interface definitions are promising. As they completely hide the underlying client/server structures, they might ultimately even supersede OPC-XML. Nevertheless, interfaces alone are not sufficient to achieve interoperability. The semantic definitions for data exchange will require more effort. This is exactly why there are so many standardization activities in the automation area.

For the end user, it may seem that just the availability of comprehensive standards like ISA S95 [18] or S88 stimulates marketing activities to convey vertical integration as a desirable automation concept. While it is certainly true that vendors waited for the adoption of a widely accepted standard before starting product development, one also has to see that the need for integration has been there before. In fact, it has been the driving force behind all standardization efforts, and it took a long time until the technological environment was mature enough to provide a solid basis. On the other hand, it appears that what has been reached today is only an intermediate step. All standardization activities had a clear focus, either from a technology or application domain point of view. The results are therefore optimized according to the respective goals but need to be properly aligned across similar or complementary activities. One such attempt is the joint working group established by ISA SP95, the OPC Foundation, and MIMOSA (Machinery Information Management Open Systems Alliance) to develop an open and comprehensive information architecture for the operation and management of manufacturing systems [53].

Despite the efforts to make standards and solutions eventually converge, there are less visionary problems to be considered and solved in the meantime. One is scalability. Automation systems tend to grow, at least as far as the numbers of data sources and sinks are concerned. Horizontal inter-enterprise integration further extends the complexity. Both the low-level data acquisition systems and the high-level data processing frameworks must be able to cope with this.

Another emerging issue not discussed in this paper is security. On the enterprise level, many solutions have been proposed in the context of e-commerce. On the field level, security concerns have long been disregarded and are not being well supported by the available technology [54]. The Industrial Ethernet movement allows for an improvement of the situation [28], but still more effort needs to be put into the definition of security policies applicable for the automation domain.

Maybe the severest difficulty to overcome, however, is not merely a technical one. Automation systems have a long lifetime. Unlike the IT world, where equipment is exchanged within a few years, automation has to cope with the existence of legacy systems. Any new solution therefore must be able to integrate existing ones in order to be economically successful. The substantial inertia of the automation area is one of the major challenges for the development of new integration approaches and considerably adds to their complexity. It is the main reason for increasingly complex middleware and abstraction layers that pave the way to ultimate integration. There will always be older technologies which need to be embraced by newer ones and cannot simply be discarded because there is still an installed base that must be supported. Technical superiority alone is not a convincing argument to renew an entire plant or an enterprise-wide planning framework. In this respect, especially vertical integration will not come about in a revolutionary manner as advertised by many automation vendors. In practice, the pragmatic approach of a steady evolution will again prevail.

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