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Advancing Smart Manufacturing in Europe: Experiences from Two Decades of Research and Innovation Projects

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Abstract: In the past two decades, a large amount of attention has been devoted to the introduction of smart manufacturing concepts and technologies into industrial practice. In Europe, these efforts have been supported by European research and innovation programs, bringing together research and application parties. In this paper, we provide an overview of a series of four content-wise connected projects on the European scale that are aimed at advancing smart manufacturing, with a focus on connecting processes on smart factory shop floors to manufacturing equipment on the one hand and enterprise-level business processes on the other hand. These projects cover several tens of application cases across Europe. We present our experiences in the form of a single, informal longitudinal case study, highlighting both the major advances and the current limitations of developments. To organize these experiences, we place them in the context of the well-known RAMI4.0 reference framework for Industry 4.0 (covering the ISA-95 standard). Then, we analyze the experiences, both the positive ones and those including problems, and draw our learnings from these. In doing so, we do not present novel technological developments in this paper—these are presented in the papers we refer to—but concentrate on the main issues we have observed to guide future developments in research efforts and industrial innovation in the smart industry domain.

Keywords: smart manufacturing; Industry 4.0; intelligent factory; smart factory; manufacturing process; technology innovation; RAMI4.0



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1. Introduction

This paper presents the main experiences and learnings from two decades of research and innovation efforts in smart manufacturing, centered on four international research projects in Europe: CrossWork, HORSE, OEDIPUS and SHOP4CF. The first three of these research and innovation projects have been completed by consortia in which we played an essential role. We participate in the execution of the fourth project at the time of writing this paper. The four projects combined cover several tens of application cases across the European manufacturing industry. In this paper, we aim at highlighting the aspects of the projects that make them successful, but also discuss issues and gaps that need to be addressed in future developments to make true smart manufacturing and smart factories a complete success.

In this introduction section, we first discuss our take on the concept of smart manufacturing, which provides the context for the main content of this paper. Next, we discuss the RAMI4.0 framework for smart industry, which we use to organize our experiences and learnings across the projects that this paper covers in a well-structured way. Then, we discuss the organization of this work as a single, informal longitudinal case study. In Section 2, we provide overviews of the four mentioned projects. We do not go into all

details (for reasons of brevity) but provide ample references to more detailed works. In Sections 3–5, we present our experience report and analyze our findings and learnings along the three dimensions of the RAMI4.0 framework, organized in main topics that we consider essential to address in smart manufacturing developments. We believe that these learnings are equally applicable to new research initiatives in smart industry and to industrial innovation and development projects. In Section 6, we provide our high-level view across the three RAMI4.0 dimensions to arrive at conclusions from a holistic perspective and conclude the paper with a summary of main observations and a brief look forward.

1.1. State of the Art in Smart Manufacturing

The concepts of smart manufacturing [1] and Industry 4.0 [2] are in practice used almost interchangeably. They are, however, not strictly synonymous, as illustrated in Figure 1 [3]. In this figure, we see that Industry 4.0 is the most important part of what is known as the Fourth Industrial Revolution (indicated by the size of the circle), but that this revolution includes more developments such as smart cities and smart mobility [4], smart logistics, smart grid and smart health. Smart manufacturing is positioned as part of Industry 4.0, which also includes overlapping concepts such as the industrial internet, the industrial internet of things [5] and intelligent manufacturing [6]. As shown in the figure, the smart factory concept is the central concept within smart manufacturing. There are other concepts included in smart manufacturing too, however, such as cloud manufacturing and IoT manufacturing (which also overlap with the concept of intelligent manufacturing).

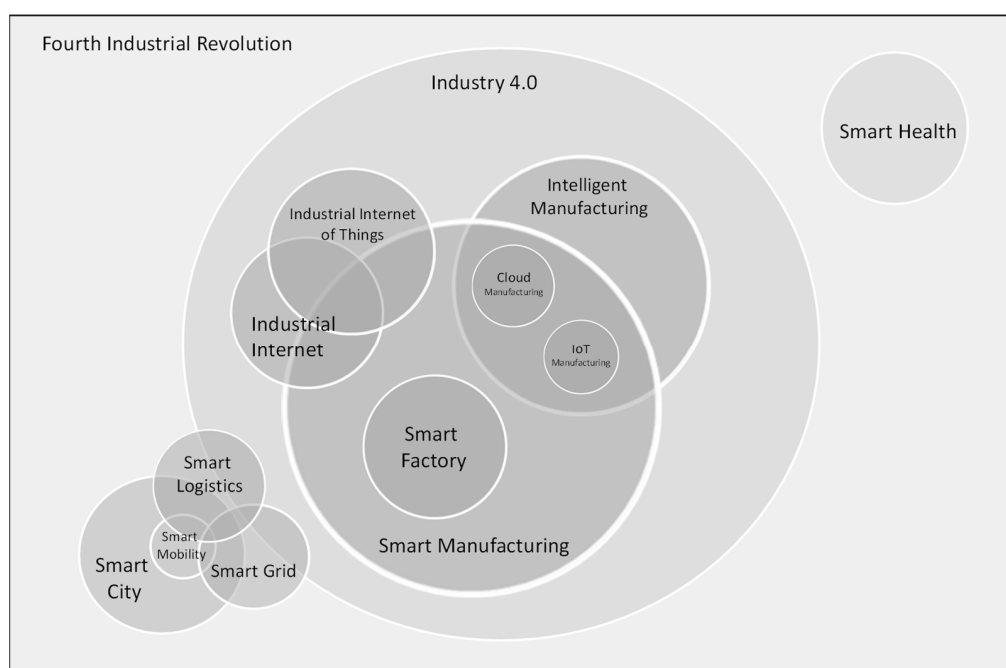


Figure 1. The concept of smart manufacturing in context [3].

The pace of the Fourth Industrial Revolution is heavily influenced by the fast development of digital technologies or technologies that have an important digital component. Examples of these technologies are flexible robots [7], automated guided vehicles, internet of things [8], augmented reality [9], blockchain, artificial intelligence and cloud platforms [10,11]. This implies that an important part of the innovation in manufacturing is shifting from the physical domain (with aspects such as mechanical engineering) to the digital domain. The projects that we discuss in this paper all have a strong digital component—but as they are applied in the manufacturing domain, they do take the physical characteristics of manufacturing into account.

In the Fourth Industrial Revolution, we also observe the development of more flexible manufacturing and delivery models. We see a growing importance of just-in-time (JIT) production models [12] that use flexibility to decrease (or even avoid) intermediate stock on the one hand and allow last-moment reaction to market circumstances on the other hand. We see a shift from traditional supply chain models that focus on the production side to demand chain models that put the emphasis on the customer side—often requiring JIT organizing, leading to mass-customization in manufacturing and “high-mix–low-volume” production. We see a growing influence of new business models, such as value and outcome provisioning instead of simple product provisioning [13,14]. The projects that we describe in this paper are contextualized by these developments.

1.2. The RAMI4.0 Framework

RAMI4.0 [15] is a leading standard framework for organizing various dimensions used to structure concepts and developments in smart manufacturing. RAMI4.0 is typically illustrated by the three-dimensional cube shown in Figure 2.

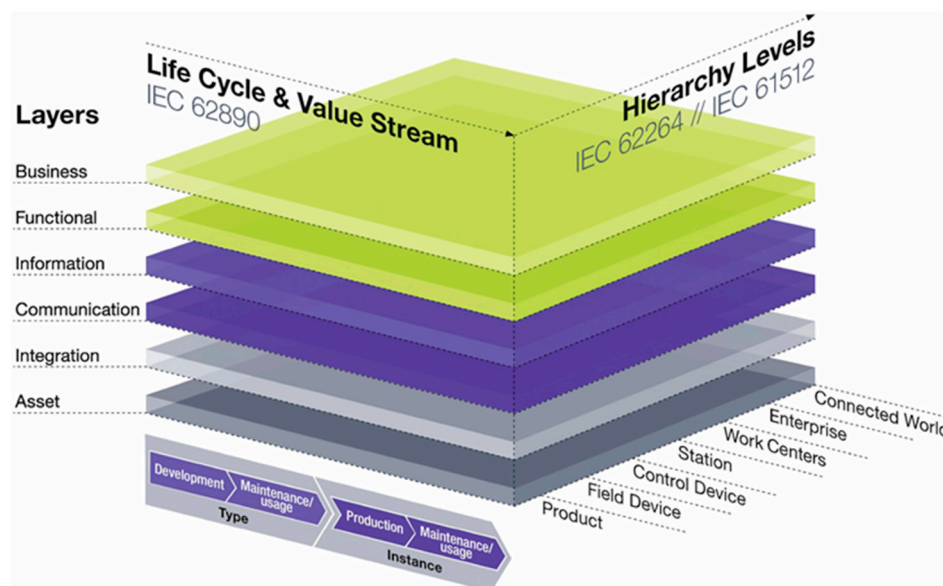


Figure 2. The RAMI4.0 framework [15]; this figure © Plattform Industrie 4.0 & ZVEI—Zentralverband Elektrotechnik—und Elektronik-industrie e.V.

As shown in the figure, the three dimensions in RAMI4.0 are labeled as *layers*, *life cycle and value stream* and *hierarchy levels*. The *layers* dimension “represents the information that is relevant to the role of an asset”. It covers the business-to-technology spectrum by relating different aspects of a manufacturing asset to layers of the enterprise architecture.

The *life cycle and value stream* dimension “represents the lifetime of an asset and the value-added process”. This axis distinguishes between the type and instance of a production system and its elements, such as the digital design of a product and its instantiation as a manufactured product. The *hierarchy levels* dimension is used to “assign functional models to specific levels” of an enterprise. This axis uses aggregation to establish enterprise levels, ranging from the connected world (i.e., networks of manufacturing organizations in their eco-systems) via stations (manufacturing work cells) to devices and products. The *hierarchy levels* dimension is related to the ISA-95 manufacturing hierarchy standard [16]. The *connected world* level is introduced above the *enterprise* level of ISA-95 to emphasize the importance of supply chain networks in Industry 4.0 (as we have seen above in our discussion of the Fourth Industrial Revolution). Additionally, lower levels are added to elaborate the control systems and equipment typically encountered in modern factories.

1.3. Method for Organizing the Content of This Paper

In choosing a method for organizing the content of this paper (i.e., our experiences in smart industry projects and the learnings from these), we have two options. The first option is to choose the method of a multiple case study, in which each of the covered projects is a case. This would imply a primary organization along the timeline of the projects, with the aspects analyzed (based on RAMI4.0 as explained before) as a secondary level of organization. The second option is to choose the method of a single case study, where we treat the projects as a continuing line of research and innovation activities of the research group of the authors. This enables a primary organization of the content along the aspects identified (also using RAMI4.0 as a basis), with the projects as a second level of organization.

As we prefer to present our learnings organized by topic rather than by time, we have chosen the second approach: we treat the work in this paper as a single, qualitative case study, covering two decades of work. This allows us to present our progressive insights by topic across the projects that build on each other. As we have actively participated in the execution of the case study, the work in this paper can be classified as an action research case study, focusing on the *what*, *how* and *why* aspects [17]. Given the duration of the covered case, our work can be classified as longitudinal research [18]. Together, we label the work underlying this paper therefore as a single, qualitative, longitudinal case study based on action research. As the analysis in this paper is an ex-post experience report over the covered projects, a full a priori qualitative case study design [19] cannot be used and the case study has an informal character.

2. Two Decades of Research and Innovation Projects

In this section, we provide an overview of our experience in smart industry research, organized in four main European projects: CrossWork, HORSE, OEDIPUS and SHOP4CF. CrossWork started in 2004 and SHOP4CF is to be completed in 2023, so together these projects represent some two decades of research into smart industry. From these projects, we draw our experiences and learnings in the next sections of this paper, organized along the dimensions of the RAMI4.0 framework discussed in the previous section. In the four subsections below, we discuss each of the four projects.

2.1. The CrossWork Project

CrossWork (Cross-Organisational Workflow Formation and Enactment) was a project in the European 6th Framework Programme for Research and Innovation [20,21]. The project ran from 2004 to 2007 and concentrated on applications in automotive manufacturing. The main results of the CrossWork project are described in detail in the book that was produced as the overall public deliverable of the project [22].

CrossWork focused on the development of concepts and technology for cross-organizational workflow formation and enactment (which explains the name of the project) in the setting of manufacturing networks. The fact that CrossWork addresses networks, i.e., the connections between manufacturing organizations, means that it is related to the concept of smart logistics (as discussed in Section 1.1 and shown in Figure 1): it supports the synchronization of activities in multiple manufacturing sites and hence the planning of transport of goods between them.

The CrossWork approach is centered around the concept of *instant virtual enterprise* (IVE), i.e., an operational collaboration that is set up between industrial organizations for a limited period of time to realize a specific business goal, such as the manufacturing of a series of products. The collaboration is modeled in an interorganizational (or cross-organizational) business process with two levels (as illustrated in Figure 3): the global level that captures the process flows between organizations and the local level that captures the process flows within individual organizations (i.e., the intraorganizational business processes). In Figure 3, the ellipses represent organizations, the arrows within ellipses represent local process flows and the arrows between ellipses represent global process flows.

In terms of the RAMI4.0 framework (which was not yet invented at the time CrossWork ran), CrossWork focuses on the interaction between the *enterprise* and *connected world* levels in the *hierarchy levels* dimension.

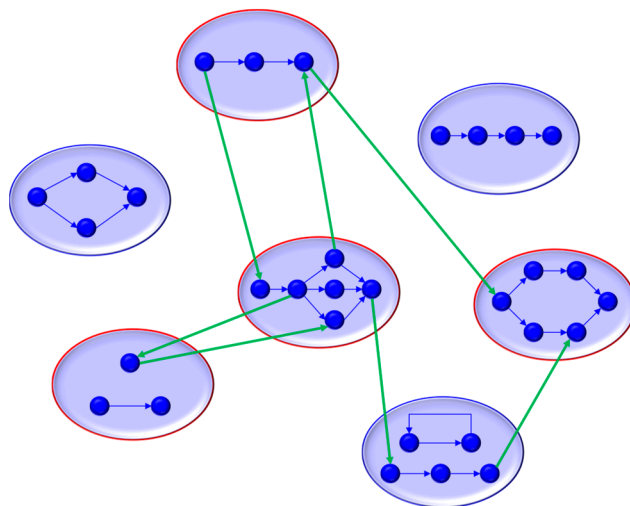


Figure 3. Two-level business model approach in CrossWork [23].

2.2. The HORSE Project

HORSE was a research and innovation project in the European Horizon 2020 program [24], running from 2015 to 2020. The full title of the project is “Smart Integrated Robotics System for SMEs Controlled by Internet of Things based on Dynamic Manufacturing Processes”, but a shorter name of the project was chosen for pragmatic reasons, referring to the analogy between a robot in modern manufacturing and a horse in old times. The focus in HORSE was twofold: safe and flexible human–robot interaction in manufacturing and integrated manufacturing process management. In terms of the RAMI4.0 *hierarchy levels* dimension, HORSE can be positioned between the *enterprise* and *field device* levels: it focuses on a single manufacturing site, possibly covering multiple production lines. As such, the HORSE project is complementary in this focus to the CrossWork project, both using a process management point of view.

The project used design science research with the purpose of generating prescriptive knowledge that can be applied in practice [25]. In doing so, it put a strong emphasis on logical architecture development [26] to create functional cohesion between diverse technical developments. Thus, a multi-aspect and multi-level approach was used, the structure of which is illustrated in Figure 4. The main results of the HORSE project are described in detail in the book that was produced as the overall public deliverable of the project [27].

The focus on safe and flexible human–robot interaction is laid down in both specific technology development and in the HORSE architecture. Specific technology includes for example mechanisms to dynamically avoid human–robot collisions in close-proximity collaboration by using 3D cameras in work cells [28]. In the HORSE architecture, a concept model was created that is the basis for the specification of collaboration between humans and robots, for example in hybrid teams. The HORSE approach integrates various advanced technologies into an integrated framework [29].

The focus on integrated manufacturing process management is laid down in a *manufacturing process management system* (MPMS) as one of the main components of the HORSE system [30]. The use of this results in a well-structured specification and execution of manufacturing processes [31] and an enhanced level of operational flexibility, most notably in the dynamic allocation of actors to manufacturing tasks and in the handling of exceptions in the manufacturing process.

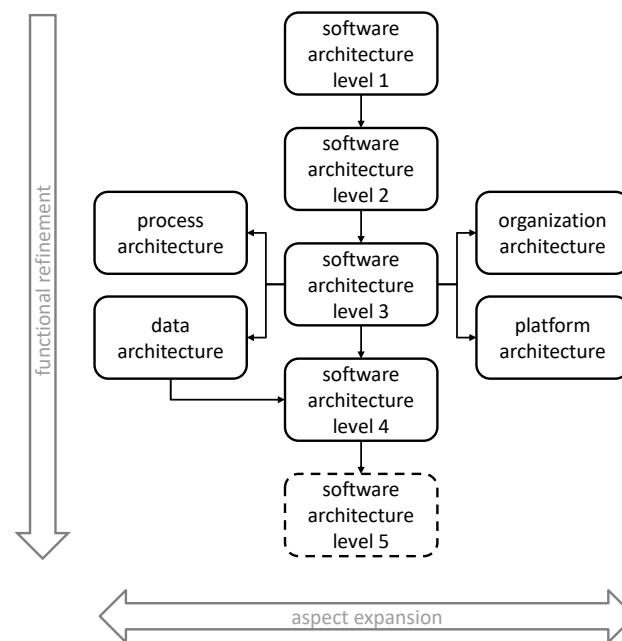


Figure 4. High-level structure of the HORSE architecture [27].

2.3. The OEDIPUS Project

OEDIPUS (Operate European Digital Industry with Products and Services) [32] was a research and innovation program funded by the European Institute of Technology under its EIT Digital overall program. OEDIPUS covered several use cases between 2017 and 2019. Within these, we were involved in the Print 4.0 use case, which focused on the application of flexible end-to-end process orchestration of manufacturing processes in smart printing factories [33]. For reasons of brevity, we will refer to this use case as the OEDIPUS project (or simply OEDIPUS) in this paper. Like HORSE, OEDIPUS concentrates on a single manufacturing site and hence can be positioned similarly in the *hierarchy levels* dimension of RAMI4.0.

The orchestration approach is implemented in a printing process management system (PPMS), which is a further development of the HORSE MPMS discussed above. Figure 5 shows an overview of the functionality of this system.

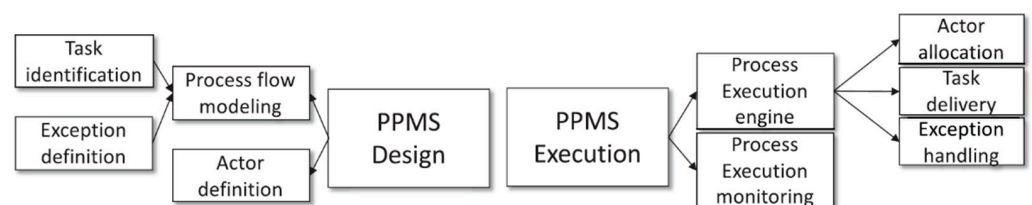


Figure 5. Overview of PPMS functionality [33].

In OEDIPUS, various developments from the HORSE project were reused, specialized from the general manufacturing domain to the printing sector. The emphasis was on the handling of on-demand, complex printing jobs that typically involve small batches, for example to serve an order for a small batch of books. To accommodate the handling of small, heterogeneous batches in printing, a special emphasis was placed on buffering, bundling and unbundling in printing processes [34]. Buffering is the collection of a batch of (intermediate) products in a process for further processing at a later moment. Bundling occurs in printing when several individual (intermediate) products are combined into a single aggregate product. An example is the packing of a batch of books into a box for

further processing (into logistics). Unbundling is the opposite, which happens for example when packs of printing paper are fed into printing machines.

2.4. The SHOP4CF Project

SHOP4CF (Smart Human Oriented Platform for Connected Factories) [35] is an EU-funded project within the eighth framework program Horizon 2020, running from 2020 to 2023. SHOP4CF aims to create a unique infrastructure for the convenient deployment of human-centric industrial applications. In the project, 20 partners develop a comprehensive software platform containing a wide range of components that cover a broad spectrum of industrial requirements, especially in the context of flexible and data-rich manufacturing [35]. SHOP4CF aims to find the right balance between cost-effective automation of repetitive tasks and involve the human workers in areas such as adaptability, creativity and agility where they create the greatest added value. In doing so, the project pursues a highly connected factory model to reap the benefits of all data generated within a factory.

To build on existing work, the SHOP4CF approach integrates and extends the results of several other projects, including the HORSE project discussed above and the L4MS project on smart logistics for manufacturing [36]. To address the focus on data-rich manufacturing environments, analytics functionality is an explicit part of the top-level functionality overview [37], as shown in Figure 6.

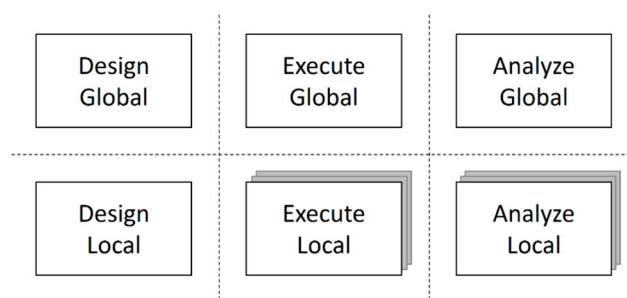


Figure 6. Top-level functionality overview of SHOP4CF [37].

After having discussed the four projects that are the “backbone” in our experience in smart manufacturing, we now move to the analysis of this experience, along the three dimensions of RAMI4.0. We start with the *layers* dimension in the next section.

3. The Layers Dimension Perspective

In this section, we analyze the four projects introduced in the previous section along the perspective of the first of the three dimensions of the RAMI4.0 framework: the *layers* dimension. This dimension includes a set of layers (shown in Figure 2) covering the spectrum from the more abstract notions at the *business* level to the more physical notions at the *asset* level. In this section, we address two topics related to this dimension that we have found to be both important and difficult in the execution of our projects. The first topic is the topic of internal manufacturing efficiency perspective versus the external customer value perspective: should we start thinking from an optimized shop floor or from a satisfied customer? The second topic is related to the OT–IT dichotomy that we have observed in our projects—and more generally in the smart manufacturing world: how is operations technology (OT) driving the physical shop floor related to information technology (IT) driving the enterprise as a whole?

3.1. Internal Efficiency vs. Customer Value Perspective

Many smart industry innovation efforts are focused on the technology perspective, i.e., on the lower half of the layers dimension of RAMI4.0. This implies that these efforts are mostly internally oriented from an enterprise point of view, focusing on making manufacturing processes more efficient (for example using lean and six sigma principles with digital

support). The competitive landscape emerging in the global Industry 4.0 development requires, however, a customer-oriented and hence external focus when innovating, represented by the upper half of the layers dimension of RAMI4.0. We see this most strongly in the current emergence of value- and outcome-based business models [13,14]. In other words, I4.0 innovation should be based on outside-in developments rather than inside-out developments.

A network-centric view was taken in the CrossWork project, but from a process orchestration point of view [20]. The approach developed for the support of *instant virtual enterprises* is centered at the external point of view (the global processes in a manufacturing network), but from a process management perspective, not from a customer value perspective. CrossWork focuses on *how* to orchestrate global manufacturing processes in a flexible way (by dynamically interconnecting local processes), not on *what* to achieve for a customer. In terms of the *layers* dimension of RAMI4.0, CrossWork is focused on the *functional* and *information* levels, not on the *business* level. This means that part of the “mechanics” for the operation of I4.0 networks have been realized in this project, but not true customer orientation.

The HORSE and OEDIPUS projects were heavily focused on improving shop floor operation by the introduction of smart industry technologies such as flexible robotics. Even though flexible shop floor operation in the end contributes to the ability to deliver customer value, it only does so in an indirect and not always focused fashion. For example, in one of the HORSE industrial cases, the emphasis of the deployment of I4.0 hardware technology (in this case flexible robotics) was initially on individual workstations in the manufacturing process to increase the efficiency of these workstations and improve worker conditions. These improvements do not directly contribute to delivering customer value. Only later in the project, when performing business model analysis, it was recognized that customer value is mostly in fast and flexible order handling, i.e., allowing supporting customized small batches with short lead times. This way of order handling is achieved by introducing I4.0 technology in shopfloor intralogistics, i.e., in flexible transport means between workstations, as well as digitizing production information and using this in end-to-end control of manufacturing processes.

Our learning from the above is that in a true I4.0 setting, it is important to start designing from unique value propositions of a manufacturing organization in its market, and from there start designing the deployment of I4.0 technologies such that this contributes most to these value propositions. This means that in smart factory design, the RAMI4.0 *layers* dimension (as shown in Figure 2) should preferably be traversed from top to bottom, not from bottom to top. In the HORSE project, activities for business strategy and business model design were planned for this in the exploitation work package and have led to valuable insights. For the activities, we have used the BASE/X business engineering method [38], which we had successfully applied in the smart mobility domain before [39]. Despite the valuable insights arising from them, these activities could have been connected better to technology development work packages. In other words, our experience shows that it is important to not concentrate only on the “how” of smart industry, but also on the “what” and the “why”—and not take the latter as an afterthought. Collaborative business models in manufacturing networks [40] play an important part in realizing flexible I4.0 scenarios.

3.2. The OT–IT Dichotomy

The bottom half of the *layers* dimension of RAMI4.0 is related to what is often labeled as *operations technology* (or OT in short) in the manufacturing world. Here, we see technology based on concepts such as PLC and SCADA, close to the characteristics of physical shop floor technology, such as robotics—nowadays often connected to IoT and cyber-manufacturing concepts [5]. The top half of the layers dimension of RAMI4.0 is related to what is often labeled as *information technology* (or IT in short) in the manufacturing world. Here, we see for example ERP and PLM systems. In practice, the OT and IT worlds

are quite distinct: there is an OT–IT dichotomy. Note that this OT–IT dichotomy is about the *nature* of systems, not about the *aggregation level* (the “size” or scope) of systems—the latter is covered by the *hierarchy levels* dimensions of RAMI4.0 (even though in practice, the OT and IT “areas” are more or less related to hierarchy levels: OT is typically located at lower hierarchy levels, IT at higher levels).

OT and IT systems obviously need to be connected to achieve true smart manufacturing—the connection should enable interoperability between systems at both the syntactic and semantic levels [41]. The need for OT–IT convergence was already recognized more than a decade ago [42]. The worlds in which these two kinds of systems are developed and deployed are quite different in practice, however: they have different experts, different foci, different jargon, different standards. This makes it often hard to close the gap implied by the dichotomy, both in terms of concepts and in terms of (standards for) technologies.

The fact that there is a multitude of technical standards available [43,44] further complicates closing the gap from the technology perspective. To illustrate, in our projects we have used standards for communication between software components such as OSGi, OPC-UA, ROS and FIWARE, where the selection was often based on existing expertise with the partners in the respective project. This even led to working with incomplete specifications available in the public domain, for example with the FIWARE Smart Industry architecture. This leads to issues in projects that pursue true vertical integration (which we consider essential for I4.0)—and these issues should not be underestimated.

The fact that terminology is different in the OT and IT worlds can also lead to conceptual issues—often related to semantic interoperability issues between systems. For example, in the HORSE project, the OT aspect was largely represented by a background in robotics in the consortium, whereas the IT aspect was represented by a background in enterprise information systems (IS) and business process management (BPM). Even though the concept of “manufacturing process” is very central in the HORSE project, it took considerable time before we realized that this concept has completely different connotations in robotics and in IS/BPM: in robotics, a process is a sequence of low-level physical movements of a robot (specified in a detailed script, e.g., in a ROS context), whereas in BPM a process is a sequence of high-level business activities (specified in a process model, e.g., in the BPMN language).

After realizing this issue in HORSE, we have addressed the challenge by creating overall manufacturing process models in a BPM style, in which the robotic scripts can be “embedded”. This leads to multilevel process models, integrating the IT and OT levels. To illustrate, Figure 7 shows a fragment (subprocess) of a higher-level, end-to-end manufacturing process, in which the activities labeled with a robot icon are robotic [27]. These robotic activities rely on the robot scripts for execution.

Problems with OT–IT integration in practice are further amplified by a heterogeneous legacy IT landscape at pilot organizations, i.e., a wide variety of pre-existing digital technologies that were not acquired with integration for I4.0 in mind. Standardization of concept models and data models (both for databases and messages) and the availability of a general-purpose software backbone (middleware) are essential for solving this issue. In the HORSE project, an approach with these components was followed in a successful way, embedded in the overall HORSE architecture design [27].

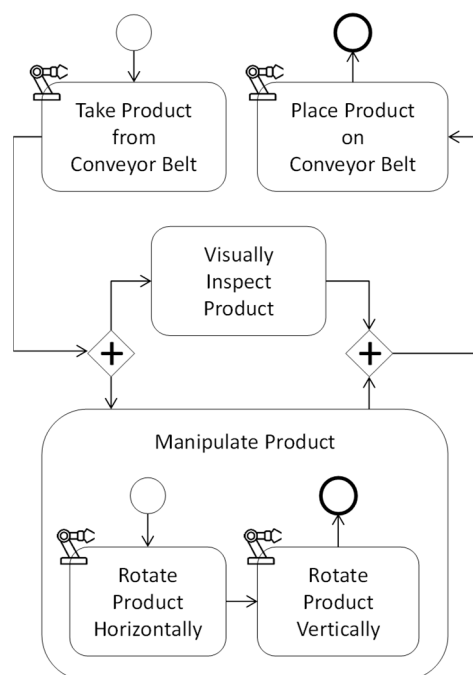


Figure 7. Fragment of manufacturing process [27].

4. The Hierarchy Levels Dimension Perspective

In this section, we move our attention to the second dimension of the RAMI4.0 framework: the *hierarchy levels* dimension. In the context of our projects, this dimension is used to indicate the organizational scope of the projects. As discussed in Section 2, the CrossWork project has an interorganizational scope, thus covering the *connected world* level of the dimension. The HORSE and OEDIPUS projects do not cover this level: they have an intraorganizational scope. The SHOP4CF project is hybrid in this respect: part of the research focuses on the interorganizational level, and another part focuses on individual shop floors and hence on the intraorganizational level. In a broader context, we observe in smart factory efforts an emphasis on the intraenterprise (or even intrafactory) levels, where interenterprise aspects are seen as part of supply chain management (SCM) [45] or logistics. As shown in Figure 1, smart manufacturing and smart logistics are mainly seen as distinct topics, but they are related under the umbrella of Industry 4.0.

In discussing our learnings from the projects along the *hierarchy levels* dimension, we focus on two issues. Firstly, we discuss the choice of how to traverse the levels of the dimension in designing smart industry frameworks and approaches: top-down (i.e., from the *connected world* level side of the dimension) or bottom-up (i.e., from the *product* level side)? Secondly, we discuss the various interpretations of the concept of *connected factory*, one of the central concepts in I4.0 thinking—and the confusion that can arise from multiple interpretations in one project.

4.1. Top-Down or Bottom-Up Design Strategy?

When designing complex systems such as smart industry systems, the question is always whether to design and engineer them in a top-down way or a bottom-up way. In terms of the RAMI4.0 *hierarchy levels* dimension, a top-down design starts at the *connected world* level (or at least at the *enterprise* level if no interorganizational aspects are taken into consideration) and uses the approach of stepwise refinement, i.e., iteratively splitting up components into their constituents. A bottom-up design starts from the *field device* level and uses the approach of stepwise aggregation, i.e., iteratively combining (or clustering) components into larger systems. A top-down approach has the advantages of leading to a well-structured architecture structure for the system and providing a “fresh start” leading to innovative insights. The disadvantages are that it typically starts fairly abstract and may

run into a “misfit” with existing systems at the lower levels (i.e., run into legacy system issues). A bottom-up design has the advantages that it starts from an existing situation (and can hence better deal with legacy system issues) and has a concrete starting point, which is often better understood. The disadvantages are important, however: the resulting system architecture may be ill-structured, and the innovation level of the design may be small. For both design strategies, a well-qualified lead architect is required: in the top-down strategy, the architect can properly handle the abstraction level; in the bottom-up strategy, the architect can channel the design into proper structure.

In the HORSE project, we have used a strictly top-down design strategy, with the five iterations shown in Figure 4. This has led to a well-structured, multiaspect, hierarchic architecture. As an illustration, part of the hierarchic structure of the architecture is shown in Figure 8 [27]. This figure also illustrates the complexity of integrated smart industry architectures.

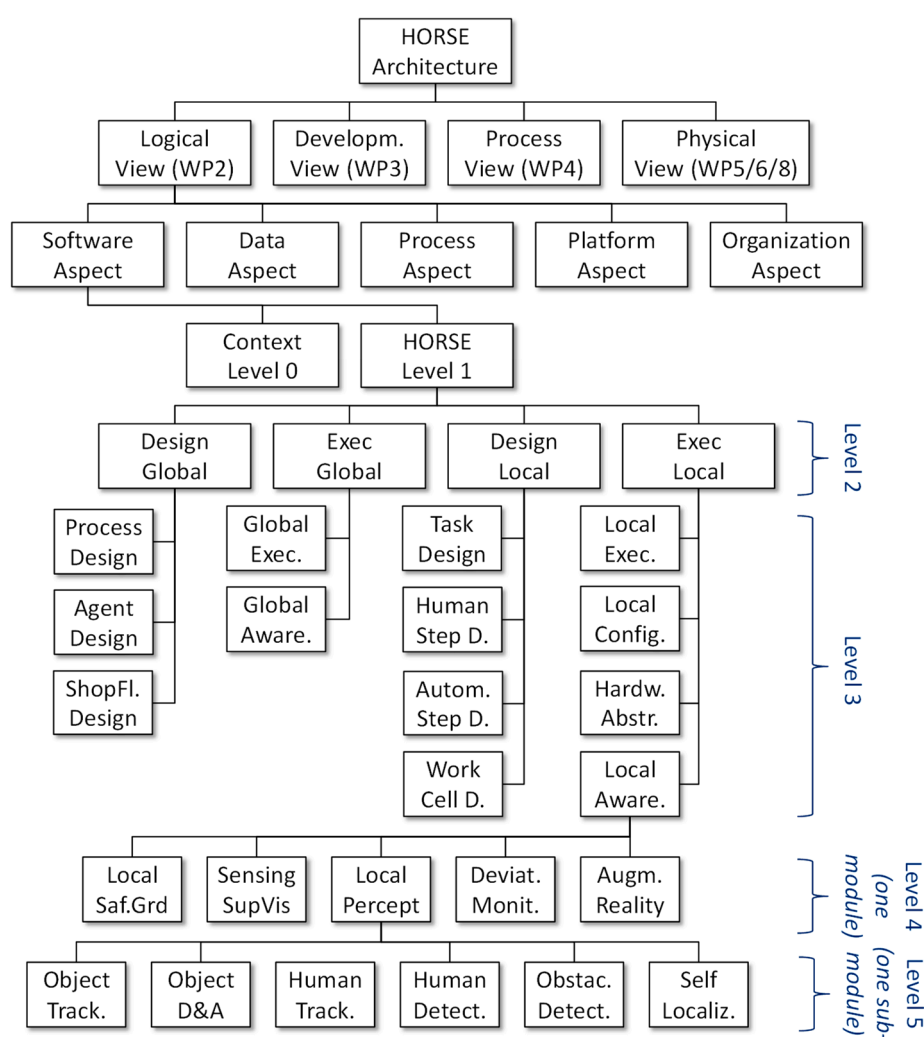


Figure 8. Part of the HORSE architecture structure [27].

The HORSE architecture has functioned as the main structuring tool throughout the project, leading to a clear overview of functionality and relatively easy integration of software in the realization phase of the project.

In the SHOP4CF project, a more bottom-up design is required by the fact that the project started with a set of nearly 30 software components that are part of the overall SHOP4CF system. Hence, a full top-down design would lead to the misfit discussed above. The bottom-up design is structured by mapping the individual software components to

the high-level architecture illustrated in Figure 6, leading to the architecture landscape of Figure 9 [37]. The landscape positions the components but is not a fully structured design for the connection of the components, like in the case of the HORSE architecture.

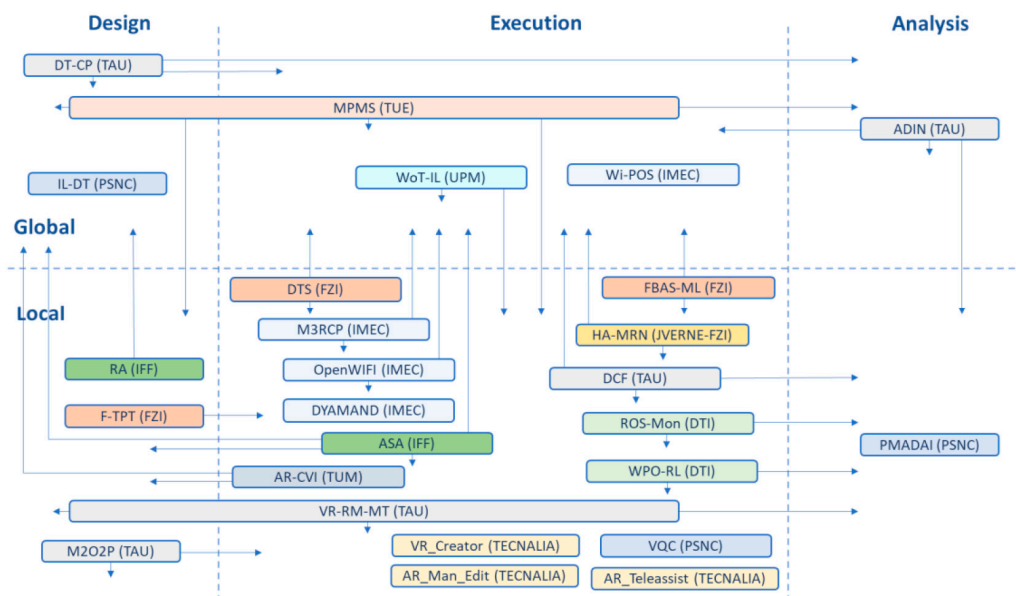


Figure 9. SHOP4CF software components in architecture landscape [37].

In many practice projects, a hybrid design strategy integrating top-down and bottom-up steps is required: the top-down steps guarantee the proper structure of the architecture (and hence of the system based on it), and the bottom-up steps guarantee the connection to existing structures. In doing so, the role of technology standards has to be taken into account explicitly: bottom-up steps introduce the risk of standard heterogeneity (leading to system complexity and possibly poor maintainability), and top-down steps introduce the risk of hard decision points with respect to standards (possibly leading to long discussions and discarding part of existing systems). A well-qualified, preferably independently positioned, lead architect is indispensable here.

4.2. The Notion of Connected Factory

The notion of *connected factory* is a popular notion in smart industry innovation nowadays (see for example [46]). Innovating towards a connected factory, it is important to be clear, however, what is exactly meant with this term. Many authors and organizations use the term for a manufacturing shop floor in which all machines, people and devices are real-time connected to improve efficiency and effectiveness of the manufacturing process ([46] is an example). In this interpretation, the connected factory is a purely intraorganizational concept, scoped to the operations of a single organization. Hence, this interpretation is not directly linked to the notion of *connected world* in the RAMI4.0 framework. The notion of *connected factory* can also be interpreted as part of the RAMI4.0 notion of *connected world*. In this interpretation, a connected factory becomes a node in a network that constitutes the connected world.

As discussed before, the CrossWork project aims at supporting connected interorganizational networks of factories and hence fits with the term *connected* as in RAMI4.0. As CrossWork focuses on business process management, the connectedness focuses on connecting business functionality, where exchange of data facilitates this. In terms of RAMI4.0 (that was not yet available at the time of execution of CrossWork), the project explicitly distinguishes in this respect between the *connected world* and *enterprise* levels of the *hierarchy levels* dimension. This is clearly visible in the CrossWork system architecture [20] shown in Figure 10, which contains two levels of business process enactment: *global enactment* takes

care of processes at the *connected world* level, and *local enactment* takes care of processes at the *enterprise* level.

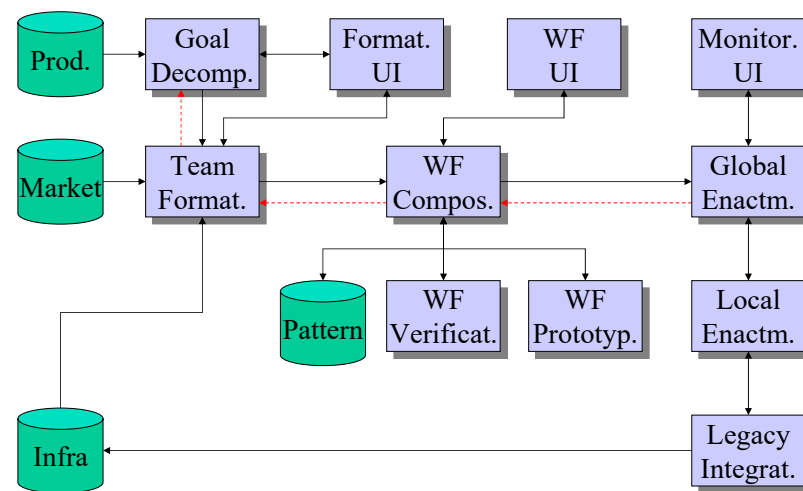


Figure 10. CrossWork system architecture [23].

The HORSE project is focused on processes within a single shop floor and does not address the *connected world* level. Hence, in the HORSE context, the term *connected factory* is to be interpreted as *connected shop floor*. The same interpretation holds for the OEDIPUS project.

In the SHOP4CF project, both interpretations of the notion of *connected factory* play a role. In the *connected world* interpretation, SHOP4CF links manufacturing organizations to a platform for retrieval of modules (shown in Figure 9), comparable to an app shop. This implies an ecosystem that is of an interorganizational kind. Interorganizational exchange of business data is under consideration in the project at the time of writing this paper. In the *connected shop floor* interpretation, SHOP4CF takes the intraorganizational point of view like the HORSE project, be it with an adapted and extended set of functional modules. This dual view on the notion of *connected factory* initially caused some confusion in the project, partly because of the fact that the project contains parties with an OT focus and parties with an IT focus and therefore a different “default” interpretation (as discussed in Section 3.2). Making this difference in interpretation clear and explicit has solved the confusion in the project on this matter.

5. The Life Cycle and Value Stream Perspective

The RAMI4.0 *life cycle and value stream* dimension addresses the functionality to support the life cycle management of products in a value stream. This covers functionality for four types of activities: product development at the product type level, product maintenance and usage at the product type level, production at the product instance level and maintenance and usage at the product instance level. These types of activities require different kinds of support, both from a system functionality and from a human capability perspective. However, shortening product life cycles, mass customization and late customer order decoupling points (sometimes even into final product assembly) lead to an integration or even “blending” of these four categories, and hence to the necessity of viewing them more holistically.

In this section, we address this more holistic view from two perspectives. Firstly, we discuss the integration of functionalities by the use of business process management as an integrator. Secondly, we look at the changing role of human actors in all these activities in an Industry 4.0 context.

5.1. Unified Business Process Management as an Integrator

When we relate the values, i.e., activities, in the RAMI4.0 *life cycle and value stream* dimension with types of software systems in a manufacturing context, we can make the following observations: Type-related development activities take place in a design environment, for instance, a computer-aided design (CAD) system, possibly supported by a product lifecycle management system (PLMS). Type-related maintenance and usage activities can be supported by a PLMS system. Instance-related production activities are typically supported by a manufacturing execution system (MES), possibly assisted by a warehouse management system (WHMS) and quality management system (QMS), and possibly with lower-level control systems with SCADA or PLC technology. Instance-related maintenance and usage activities can be supported by a variety of system types. Many of these systems include some form of process support, i.e., functionality to perform functions in the right order—either in a straightforward linear way or a more advanced way. However, these forms of process support are often isolated in their respective systems, making it hard to have overall, end-to-end process control in a dynamic smart industry context.

Therefore, in the HORSE project, we have developed unified business process management (UBPM) as an approach to deal both with design-time complexity and run-time dynamism in smart manufacturing, both at the process type and process instance (case) levels [30,31,47]. UBPM puts one central manufacturing process management system (MPMS) in control of the entire manufacturing process [47,48], as illustrated in Figure 11. In this way, all other systems are “driven” by the MPMS, which activates their functions where necessary.

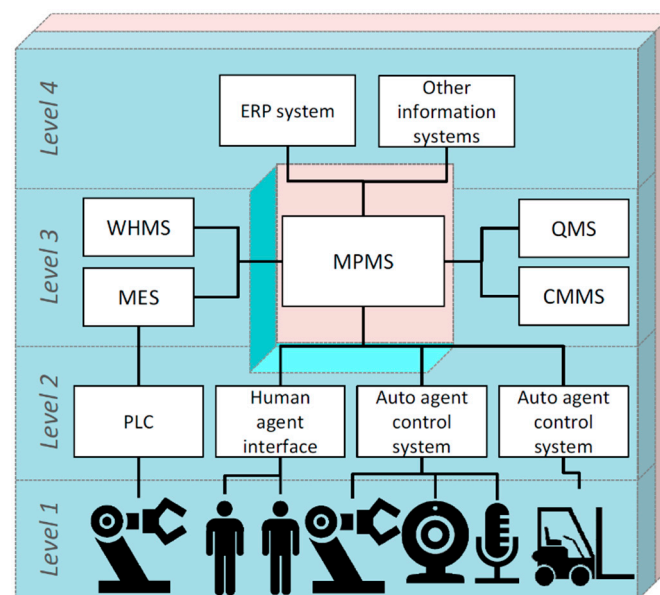


Figure 11. MPMS in the context of unified business process management [48].

Our experiences with the UBPM concept and prototype implementation have been positive. We have observed a problem, however, in the relation between process control and shop floor planning (or manufacturing resource planning (MRP) [49]) at the operational level. In other words, we have found a functional disconnect between the UBPM approach (end-to-end process orientation) and operations research (OR) domain (resource or function orientation). This has led to discussions in practical applications in the HORSE project about flexibility in production schedules, constrained by physical shop floor layout and machinery flexibility (also with respect to tool change times). These discussions have not yet led to a generally applicable solution to close the observed gap at the time of writing this paper: a general, functional interface is required between planning systems and process control systems, where the question is which system is in charge: does a process control

call a planning system for local planning decisions, or does a planning system call a process control system for executing plans?

5.2. The Changing Role of Human Actors

The role of human actors in manufacturing is changing through the advent of advanced technology [50]. In our projects, most notably HORSE, OEDIPUS and SHOP4CF, we have directly observed this changing role of human actors in manufacturing processes. We see this change in two main aspects: on the one hand in the evolution of humans from task performers to task supervisors and on the other hand in the fading gap between human and robotic workers.

Human actors are increasingly changing role from task performers to task supervisors, where machines (robots) take over the physical performance of the task. Reasons for this can be found in the need for improving the efficiency of the manufacturing process or improving working conditions (the latter in case of physically demanding or very repetitive tasks, or in situations that are a health hazard). In a robotized factory, only incidental or complicated tasks remain for human execution. Incidental tasks may occur in exception handling, for example when a robotic solution breaks down and a human operator has to take over temporarily. Complicated tasks are those where a robot does not have the right abilities (for example in precision or in degrees of freedom of movement) or where programming the robot would be overly complicated.

We also have observed a shift in decision-making from human actors to automated actors, in all four kinds of activities discussed in the introduction to this section. Here, systems (based on diagnostic or predictive technology) prepare decisions and humans finally decide or only intervene when things go wrong. A typical example from the shop floor is the task of visual quality inspection from one of the HORSE case applications: here, an automated system can perform visual inspection by interpreting camera images of products, where a human actor interferes only when the system cannot decide.

In all of this, the “gap” between human actors and automated actors is fading. While in traditional manufacturing environments, humans and robots are often strictly physically separated (for example by fences), we are moving to more mixed, collaborative scenarios. We observe this in the emergence of collaborative robots (also known as *cobots*) [51], human–robot teams and even hybrid actors. A hybrid actor is a single active entity that consists of a human and a robot, for example a human wearing a robotic exoskeleton for lifting heavy objects. This development implies that human and robotic actors should partly be flexibly treated in an “exchangeable” way. In the HORSE project, we have laid the groundwork for this by an agent concept model that integrates both types of actors (and combinations of them) and by a flexible resource allocation or role resolution mechanism [48,52] that can dynamically decide which actor to assign to which manufacturing task.

The HORSE agent concept model [27] is shown in Figure 12 (where arrows denote specializations). In the top-left corner of the figure, we see that the concept of *agent* is specialized into *human agent* and *automated agent*. Both types of agents can be part of a *team*, i.e., a collection of agents that performs a task in a work cell (for example, a human worker assisted by a robot for heavy lifting). A *human agent* and a *robot* (as a specialization of *automated agent*) can be combined into what in the HORSE context is called a *cobot* (so a more specific interpretation of the term than the more general notion of *cobot* introduced before).

industrial manufacturing practice (i.e., other than the innovation projects discussed in this paper) supports this observation.

Table 1. Summary of learnings from two decades of projects.

Dimension	Aspect	Main Learnings
Layers	Balancing internal efficiency and external value	The emphasis is often too much on internal efficiency. Analyze business strategy and business model early in innovation projects.
	Handling the OT-IT dichotomy	Systems are poorly vertically integrated. Connect them by shared concept and data models and a clear middleware approach. Use standards.
Hierarchy levels	Choosing between top-down and bottom-up design	Both strategies have their pros and cons. Make explicit choices, led by a well-qualified, independent architect.
	Understanding the concept of the connected factory	There are two different interpretations with OT and IT perspectives, respectively. Be innovative. Make choices clear and explicit in an innovation effort.
Life cycle and value stream	Applying unified manufacturing process management	Functions are too separated. Consider unified business process management as an integrator, link to planning functions.
	Dealing with the changing role of human actors in the factory	The gap between human and robotic actors is fading. Treat both types of actors in a common framework to enable flexibility.

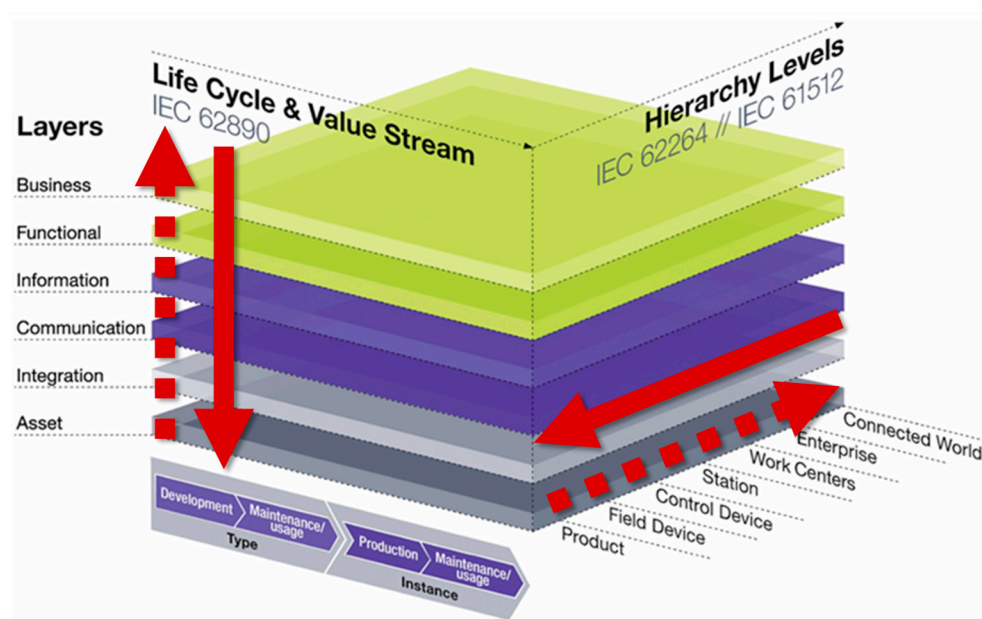


Figure 13. Industry 4.0 design directions in RAMI4.0 (adopted from [15]; this figure © Plattform Industrie 4.0 & ZVEI—Zentralverband Elektrotechnik—und Elektronik-industrie e.V.).

Based on the experiences and learnings reported in this paper, we continue the development of novel approaches and technologies in the SHOP4CF project, contributing to the future of smart manufacturing. We are convinced that structured approaches to deal with complexity and dynamism in smart manufacturing will be a key factor for success, as complexity and requirements for flexibility will only grow in the future. In this paper, we have positioned our work in the context of Industry 4.0. Future work will also be positioned in the context of the newly launched Industry 5.0 concept [53], which is centered on the qualities of industrial sustainability, human-centricity and industrial resilience. We have

covered human-centricity in our work so far (most explicitly in the HORSE project), as well as industrial resilience by explicitly factoring in process flexibility in our approaches. Sustainability has been less of an explicit concern in our approaches so far but does require adequate attention in future work.

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