Cognitive Technologies

Wolfgang Wahlster *Editor*

SemProM

Foundations of Semantic Product Memories for the Internet of Things

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Foundations of Semantic Product Memories for the Internet of Things

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Foreword

Information and Communication Technologies (ICT) are the number one driver of innovation. They are responsible for more than 80 % of innovations in the industries and fields of application in which Germany is particularly strong—the automotive sector, medical technology, and logistics. The Federal Government's High-Tech Strategy 2020 therefore puts ICT among the key enabling technologies that will play a decisive role in the future viability of the German economy.

In the Federal Government's High-Tech Strategy 2020, research funding focuses on five fields of action: climate/energy, health/nutrition, mobility, security and communication. Key technologies, including information and communication technologies, form the basis of new products, processes and services which can contribute to meeting the challenges that our society is currently facing. Digital Germany 2015, the Federal Government's ICT strategy, is a comprehensive strategic program for the area of ICT. The research topics are addressed in the Federal Ministry of Education and Research (BMBF) funding program "ICT 2020—Research for Innovations."

The key prerequisites for innovations in these areas are (applied) research and development results in the fields of electronics and microsystems technologies, software systems and knowledge processing, communications technology and networks. ICT funding focuses on three strategic research and development areas: "ICT in complex systems" (e.g., embedded systems), "new business processes and production methods" and "the internet of things and services." In this context, it is important to concentrate on the quality-based goals of efficiency, security, user friendliness and resource efficiency. This is the only way in which the strengths of German ICT research and the traditionally high international standing of German engineering can be transferred to ICT solutions from Germany.

New instruments are being used for the ICT 2020 program. Innovation and technology alliances are being forged as a way of building bridges between technology development and application. Support for SMEs is being provided in the form of funding for cooperative R&D projects across different information and communication technologies, simplified funding procedures, the establishment of a central contact point, and shorter periods between submitting applications and the final funding decision/provision of funds.

The main fields of application of the ICT 2020 program are:

- automotive, mobility
- mechanical engineering, automation
- health, medical technology
- logistics, services

This was the starting point for the research activities in the joint project SEMPROM—*Products Keep a Diary*. Coordinated by the German Research Center for Artificial Intelligence in Saarbrücken, a consortium of four well-known large-scale industrial companies, two middle-sized companies, and one research institute was formed. The objective of SEMPROM was to conduct fundamental research in the area of *Semantic Product Memories for the Internet of Things*. The results of SEMPROM form key components for the development of *cyber-physical systems* in the context of the new *Industry 4.0* paradigm.

Thanks to the dedication of all project partners SEMPROM's ambitious objectives have been more than accomplished, as for instance:

- cross-industrial effects by the digital product memory from production to logistics until the end-user were illustrated,
- integrated solutions are now available for fine-grained information communication over the entire lifecycle of a product (open-loop), and last but not least
- basic principles for the standardization of digital product memories were laid down.

Moreover, the know-how gained in the project was protected for the German economy through 9 patent applications, 10 spin-off products and three spin-off companies so far. In the scientific area, the SEMPROM project resulted in 69 publications, 23 diploma theses and six Ph.D. theses. SEMPROM was funded with 16.46 million € between February 2008 and January 2011.

This book provides a comprehensive overview of the broad spectrum of results of the research conducted in SEMPROM. I thank and give credit to everyone involved in the project but especially to Dr. Rainer Jansen, principal precursor in the field of Industry 4.0 and my predecessor in accompanying the project on behalf of the BMBF, as well as to Professor Wolfgang Wahlster for his professional project management and his competent scientific leadership of the distinguished team of researchers.

Bonn, Germany

Dr. Erasmus Landvogt
Head of the IT Systems Division
German Federal Ministry of Education and Research (BMBF)

Preface

A book such as this could obviously not be put together without the help and cooperation of many people.

I am particularly indebted to the authors who graciously made their contributions available in a timely fashion.

I would like to thank Dr. Anselm Blocher for his excellent editorial assistance and the production of the final camera-ready copy. Special praise goes to Mona El Hadidy and Renato Orsini for their assistance in formatting and copy-editing the book. Special thanks go to Ronan Nugent from Springer for his continuous publication support.

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Saarbrücken, Germany
Wolfgang Wahlster
Scientific Director of the SEMPROM Project
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Contents

Part I Introduction

Part II Platforms for Building a Digital Product Memory

Part III Modeling and Processing Digital Product Memories

Part IV Multimodal Interaction with the Digital Product Memory

Part V Applications of Digital Product Memories

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Part I
Introduction

The Semantic Product Memory: An Interactive Black Box for Smart Objects

Wolfgang Wahlster

Abstract Low-cost and compact digital storage, sensors and radio modules make it possible to embed a digital memory into a product for recording all relevant events throughout the entire lifecycle of the artifact. By capturing and interpreting ambient conditions and user actions, such computationally enhanced products have a data shadow and are able to perceive and control their environment, to analyze their observations and to communicate with other smart objects and human users about their lifelog data. In the introductory section of this chapter, we illustrate the innovation and application potential offered through the concept of semantic product memories by an imaginative scenario. Then we provide a taxonomy of the wide variety of digital object memories: from mobile cyber-physical systems to semantic product memories in open-loop applications. We show that extended customer information, traceability and increased quality assurance have been the drivers for the rudimentary forerunners of product memories in the food industry. Then we discuss the benefits and risks of semantic product memories for producers as well as consumers. We argue that active semantic product memories will play a key role in the upcoming fourth industrial revolution based on cyber-physical production systems. Finally, we provide an overview of the structure and content of the remainder of this book.

1 A Future Scenario for Semantic Product Memories

Embedding sensors, communication and computing capabilities into physical products enables them to seamlessly gather and use information throughout their entire lifecycle. By capturing and interpreting user actions and ambient conditions, smart products with a data shadow stored in their embedded digital product memory are able to perceive and control their environment, to analyze their observations and to communicate with other objects and human users about their lifelog data. Although the term “Digital Product Memory” was coined by the author already in Wahlster

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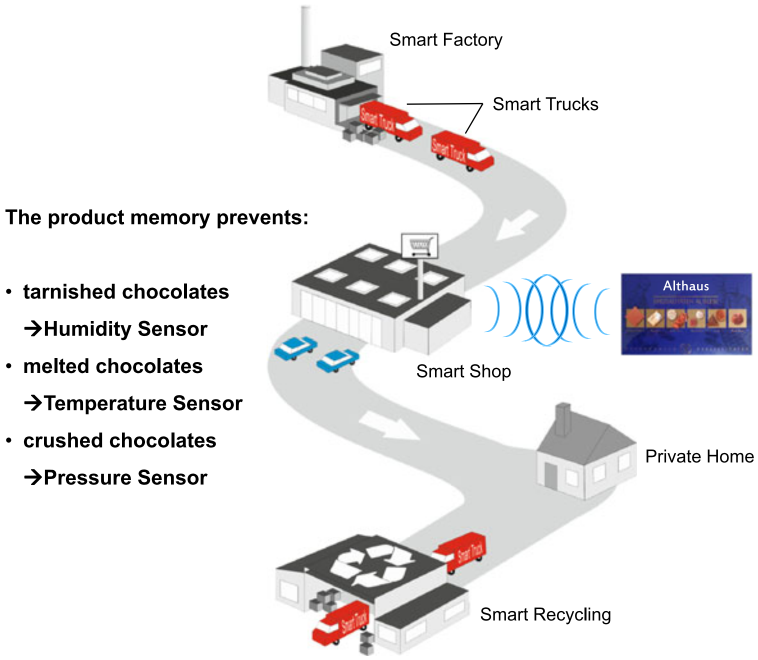

Fig. 1 Semantic product memories covering the complete lifecycle of products

(2007), only after the successful implementation and the deployment of industrial applications developed by the SemProm (**Sem**antic **Pro**duct **M**emory) consortium is it now in widespread use and has become widely known both in academic and industrial circles. In the following introductory paragraphs, we will illustrate the innovation and application potential offered by the concept of semantic product memories presented in this book through an imaginative scenario.

Imagine a company named Althaus produces exclusive Belgian chocolates and creates a new limited-edition series of pralines in fancy gift boxes that use a semantic product memory (Fig. 1). The House of Chocolates in Berlin has just ordered via the B2B web service offered by Althaus 20 boxes with a special selection of gourmet pralines based on ganaches of red fruits for their Easter promotion. This is a typical low-volume, high-mix production order for the smart factory of Althaus. The first production step is to initialize the semantic memories of the gift boxes with the number and types of gourmet pralines that have to be filled into the boxes by the automatic filling machine modules along the conveyors. The semantic product memories will tell the filling modules at each filling station which kind of praline from the large variety of Althaus pralines should go to a certain position in the gift box. This information flows directly from the order management system of Althaus into the semantic product memory of 20 gift boxes of the specified size according to the order from Berlin. After filling in the pralines, a special promotion label for the Berlin store is printed according to the specification in the product memory and attached to the gift boxes by the labeling machines of the smart factory.

After manufacturing, the gift boxes have to be shipped to Berlin. Since it is a very hot spring day, the very expensive luxury pralines filled with red fruits must be refrigerated and the temperature and humidity has to be checked during the trucking period by DHL's temperature-controlled fleet. Althaus and the House of Chocolates can both access the web services provided by DHL's real-time logistic information hub allowing for temperature and humidity surveillance (Ulrich et al. 2013). However, the temperature sensors embedded in the semantic product memory of the gift boxes detect a sharp temperature rise during a short break of the truck driver on a parking lot and immediately "complain" by machine-to-machine communication to the truck's refrigerator to increase cooling. In addition, Althaus asked DHL to use one of their security boxes with a semantic product memory, since they wanted to be absolutely sure there would be no loss during transport. With a PIN/TAN for the box and the ability to detect any opening of the security box during the trip Althaus has made sure that only the intended recipient in Berlin is able to open the case.

When the shipment finally reaches the House of Chocolates in Berlin, the owner opens the security box with the PIN/TAN that he received from DHL and checks the semantic product memories of all 20 gift boxes before accepting the delivery using his NFC-enabled smartphone. Although the gift boxes show no direct sign of damage, it turns out that one of the boxes shows a violation of the maximum pressure limit in the lifelog stored in its semantic product memory. Probably during the loading of the praline gift boxes into the security box, this box was pushed too hard. By comparing the time stamps of the related measuring event of the product memories in the gift box and the closing of the security box together with the positioning information for both memories the mishap can be verified. Since the store owner in Berlin does not want to sell potentially crushed pralines to his discerning customers, one out of the 19 boxes is not accepted and shipped back to Belgium.

On the next day, when Wolfgang is looking for an Easter gift for his aunt Mary, he is browsing the shelves of the House of Chocolates for some nice Belgian pralines. He grabs two gift boxes off a shelf with luxury pralines and a window pops up on a display embedded into the shelf showing a comparison between the two products. The gift box from Althaus contains fresher pralines according to the information from the semantic product memory and the pralines have fewer calories than the competing product. Although for 32 Euros the pralines are quite pricey, Wolfgang decides to buy them and puts the Althaus pralines into his shopping cart. Immediately, this item is tagged as being bought in the electronic shopping list on his smartphone. When he is leaving the shop, Wolfgang goes through the Easy Checkout system (Kahl et al. 2013). No product scanning is required at the cashierless checkout station; only the relevant contents of the semantic product memory are read. Wolfgang uses his BMW car key with its embedded contactless credit card function for automatic payment, since he wants to rush home with his pralines during the very hot afternoon.

When he arrives at his BMW in the parking lot and places the gift box on the backseat, the car's indoor sensors detect the praline box and read its semantic product memory. A temperature threshold for the pralines is found and displayed in the car's dashboard display. A personalized service is offered by the navigation system that suggests using the fastest route home and turning the car's air-conditioning to the maximum in order to avoid a temperature violation for the praline (Kahl et al. 2013).

Before Wolfgang visits his 80-year-old aunt Mary on the Easter weekend, he uses his NFC-enabled smartphone to check again the semantic product memory of the gift box. He makes sure that the humidity, temperature and pressure sensors have detected no violations while the box was stored in his home. Without breaking the seal of the gift box, he wants to make sure that the pralines are not tarnished, were not melted and are not crushed, since he does not want to disappoint his aunt. When he presents the gift, Aunt Mary is very excited, since she loves Althaus pralines, and she opens the box immediately. However, her Medivox system that she always carries along is beeping and displaying a warning message: she should take her anti-diabetic pills right now and then wait 30 min before eating a praline. The Medivox system has read the semantic product memory and knows about Aunt Mary's type II diabetes and her medication.

In addition, the semantic product memory provides the information that all the pralines in the box contain traces of hazelnut. When Aunt Mary later offers a praline to her visiting friend Paul, he uses the NFC reader of his smartphone to check the praline box for any of his food allergies. His personal allergy app warns him to not eat these pralines, since he is allergic to hazelnuts and the app has found hazelnuts as one of the product ingredients mentioned in the semantic product memory of the Althaus gift box. Paul apologizes to Aunt Mary that he cannot accept her kind offer.

One week after Easter, all pralines are gone and Aunt Mary throws the nice gift box into the trash can. At the recycling plant this specific instance of semantic product memory embedded in the praline box is used for the last time (Fig. 1). The automatic sorting module recognizes the embedded system, a robotic gripper communicates with the product memory to locate the position of the black box and separates it from the rest of the box for recycling electronics. Finally, the remaining box is used for recycled paper production. This concludes the lifelog of the praline gift box and our story.

This scenario illustrates the lifecycle from production to consumption and finally recycling (Fig. 1). Our SEMPROM project has realized all the uses cases presented in this scenario in concrete demonstrators and fully operational prototype implementations. Thus, although the story is somewhat contrived, we are not talking about science fiction here, but about realistic application potentials for semantic product memories in the near future.

The underlying story in the presented scenario has shown that semantic technologies for product memories must guarantee interoperability of the product memory during the complete lifecycle of smart objects and enable ubiquitous access to the product's lifelog: the artifact can tell the story of its life at any time to other objects and human users in an understandable way. The scenario underlines the fact that semantic product memories must operate with high levels of reliability, robustness, safety, security, trust and usability.

As our scenario has shown the Internet of Things will not be a separate entity in parallel with our human world of Internet information and the Internet of Services.

All three will co-exist and, as our example shows, be intimately bound up with each other.

2 Active Digital Object Memories as Mobile Cyber-Physical Systems: A Taxonomy

A semantic product memory stores a digital diary of an individual physical object in a persistent way and makes this information available to its environment by wireless communication. In this book, we present a great variety of semantic product memories with a wide spectrum of technical realizations in various fields of application that were designed, implemented and tested in the SEMPROM project.

An embedded product memory has primarily the function of a black box in airplanes, and, like a flight recorder, stores all relevant ambient parameters in digital form. Modern commercial jetliners store data for 3,000 (B737) to 10,000 (A380) parameters sampled eight times per second, so that on a single cross-country flight a Boeing 737 generates 240 terabytes of data. This is already big data, but manufacturing industry stores more data than any other sector: in 2010 close to 2 exabytes of new data were stored in central log files of factory control systems. Thus, semantic product memories play a crucial role in distributed data acquisition and integration architectures.

The most advanced of today's embedded systems are so small that they can be built into any everyday object in such a way that they cannot be seen from the outside. The lifelog includes time-stamped information about the relevant events in all phases of the product lifecycle, so that at every phase of its life the product can "tell the story of its life" till its end in a recycling center or waste processing plant. The digital shadow realized by a semantic product memory establishes a simple kind of self-awareness for a product, since it can access its context and its own history like a very basic episodic memory.

Before we introduced the notion of digital product memories, we worked for many years on the automatic construction, exploitation and sharing of personal journals for people. Systems like Specter (Kröner et al. 2006) or SharedLife (Wahlster et al. 2008) create a digital episodic memory for a person, in which all events noticed by the system's sensors as well as conclusions drawn based on these events are stored. Since ideally the recording time covers the user's life span, a large-scale data structure is required, which provides the user with appropriate means for accessing all the varying data. Some of our insights on lifelogging for people could be transferred to the lifelogging of products in the SEMPROM project.

Semantic product memories form a subclass of Digital Product Memories (DPMs, Fig. 2). Digital product memories provide machine-readable information about the product lifecycle, whereas semantic product memories go beyond that, since they provide a machine-understandable meaning description of their contents based on semantic web technologies (Fensel et al. 2003). If a product memory has no explicit semantic markup, only propriety software can exploit the information

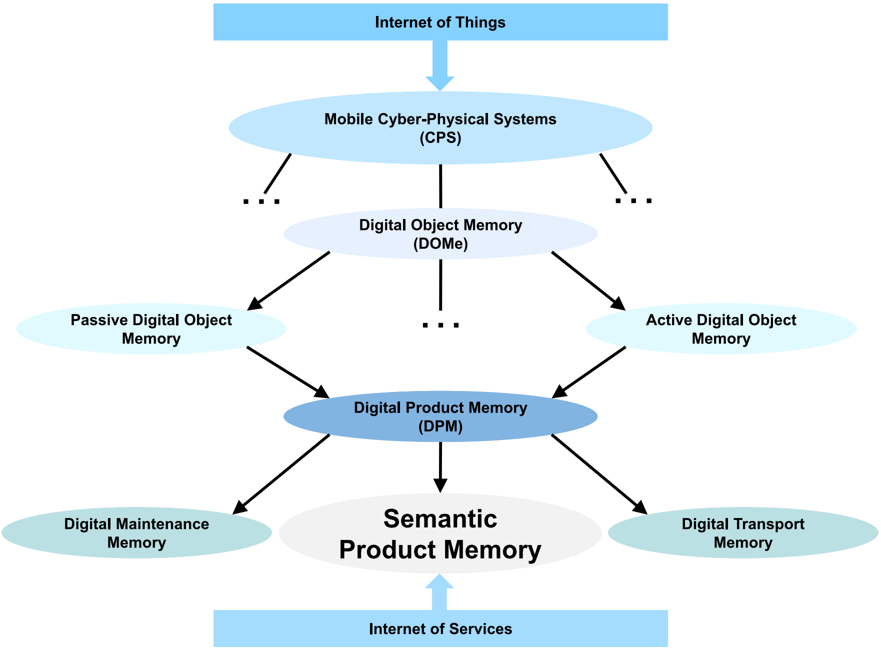

Fig. 2 A taxonomy of digital object memories

stored in the memory. In contrast, semantic product memories can be interpreted by any software that has access to the semantic description of the epistemological primitives and the ontologies used for capturing memory contents. If a product remains under the control of a single company or corporate group during its lifecycle, the use of ad doc data formats without formal machine-understandable semantics for digital product memories is possible, since in such a closed-loop system a uniform interpretation of the stored information can be enforced as an in-house standard (Fig. 3). However, in today's networked economy with its growing business web such closed-loop chains are no longer possible, since the product will be handled by many different stakeholders during its lifespan. Thus, open-loop applications of digital product memories become necessary (Fig. 3). In this case, semantic data formats ensure the accessibility of the semantic product memories for an unrestricted and unpredictable community of commercial and private users during the product's life.

The term "Digital Product Memory" was coined by Wahlster (2007) and then used by the ICT strategy committee of the German Federal Ministry of Education and Research (BMBF) chaired by the author for drafting the research funding program ICT 2020 (BMBF 2007). This program suggested a technology alliance for digital product memories as a cluster of projects with a focus on advanced logistics (see p. 35 in BMBF 2007). SemProM was the first project funded in this part of the ICT 2020 program.

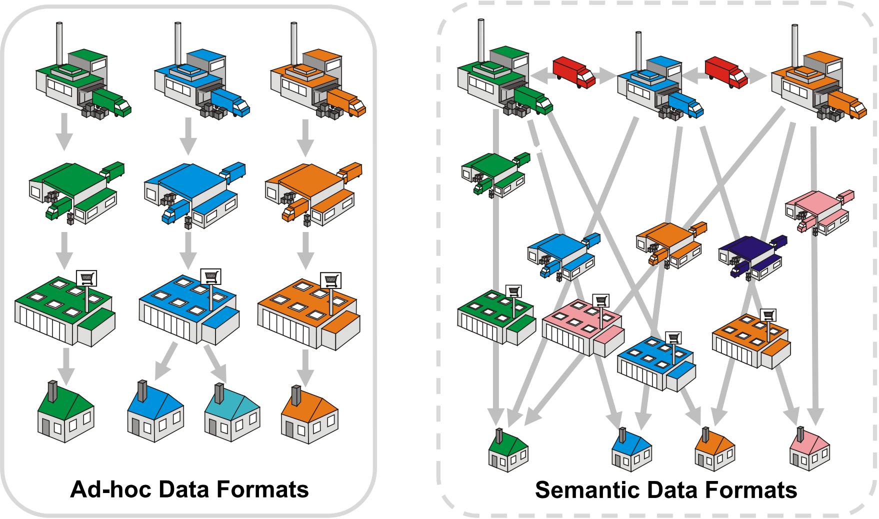

Fig. 3 Closed loop versus open loop product memories

The technology for digital product memories has been developed primarily for tangible objects that have been created by humans and/or machines as finished goods from raw materials, such as cars, washing machines, and manufacturing equipment. However, the concept can also be applied to agricultural products and food. For intangible products like an insurance policy or a vacation package this notion is not directly applicable. Although in principle immovable objects like bridges, walls and houses could also be augmented with a digital product memory such use cases have not been considered by us in our SEMPROM project.

Digital product memories are a subclass of digital object memories (Fig. 2), which include memories for all artifacts that were intentionally created such as containers and pieces of art or valuable and rare natural objects such as a marble plate or a lump of gold. Such objects do not have all the attributes of industrial products, but nevertheless a digital black box attached to them for lifelogging can make sense for specific applications. The first international workshop series about the generalized notion of a Digital Object Memory (DOMe) was established by members of DFKI's SEMPROM team in 2009 and is now an annual event in conjunction with the ACM conference series on ubiquitous computing.

A full-fledged digital object memory embedded or attached to a physical object includes on the hardware side

- a microprocessor,
- memory,
- microsensor systems,
- positioning chips,
- radio modules for web connectivity,
- possibly actuators, and

- its own energy supply or energy-harvesting unit.

On the software side there are

- memory management functions,
- sensor interpretation components,
- and possibly sensor fusion software modules,
- state transformation and processing logic components,
- communication interfaces,
- user interfaces, and
- security modules.

Such a high-end digital object memory with a combination of sensing, computing and communicating capabilities embedded deeply into a physical object can even cause a change of the state of the physical environment, for example when the temperature of a refrigerated truck trailer is decreased due to a detected threshold violation of an object memory in that transporter. This represents a typical example of a mobile cyber-physical system that bridges the virtual and the physical world. In addition to the capabilities needed for realizing advanced digital object memories, general cyber-physical systems have some design features like self-organization, decision making under uncertainty and partially autonomous behavior that are not essential for the basic functionality of digital object memories.

Although for an individual digital object memory it is impossible to fully monitor or control its physical substratum, the coordinated communication and action of networked digital object memories within an instrumented environment has the potential for unprecedented capabilities of smart systems.

Digital object memories are basic building blocks for the Internet of Things (IoT) connecting digital information with physical objects—which transforms an artifact from being a passive object into a smart object that may store data, link to related data and even offer data or services to human or machine consumers. For a person's digital memory in lifelogging applications, it is useful to distinguish between the recorders and users of information (Czerwinski et al. 2006), for example in a biography versus an autobiography or a babysitter report to the parents versus a personal diary. In digital object memories the information is recorded by the object itself and used by others, except for active product memories (see Sect. 5) that use their own memory for action planning.

Deep ontological questions occur when a complex product that is assembled from many components comes with a hierarchy of embedded product memories. In the future, the black box of a car may contain a link to the product memory of its motor. But what happens when a new motor is installed? How can the consistency of the memories of the parts and the overall product memory be guaranteed? Should all the information from the component memories be inherited by the memory of the complete product? What happens when a complex product is split up into pieces? Should the original product memory be copied and be included in every piece? In SEMPROM, we introduced *part_of* and *has_ part* relations in the memory model, so that project memories can be nested. However, currently the update and synchronization of inherited memory information after changes such as assembly,

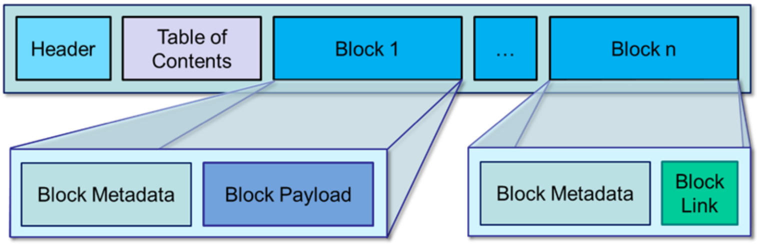

Fig. 4 The structure of the object memory model

disassembly or modification must be triggered manually. In this way, a refurbished component that is reused in a new complex product may recall from its memory in which products it was installed previously.

In SEMPROM, the proposal OMM (Object Memory Model) for a very flexible block-based semantic product memory model was specified in a W3C incubator group[1] using XML as a basis. The proposed object memory format partitions an object memory into several blocks (Fig. 4). Each block contains a specific information fragment and provides a set of metadata for search tasks in the memory. This list of blocks is supplemented with an optional table of contents and a header section. This header specifies the version of the OMM, a primary unique identifier ("primary ID") for this object memory and an optional link to additional external block sources. Each object memory block contains information about a specific aspect or phase of the product's life. For the identification of relevant blocks by users and applications a set of block metadata indicates the block's topic, which is stored in the block payload. If the block payload is not embedded directly into the XML structure, then a link can be provided to indicate a relation to an outsourced block payload at any location (Haupert and Schneider 2013). The block payload is the information container for the product memory entries and ideally is encoded in semantic web languages like RDF or OWL, so that a machine-understandable ontology and standardized epistemological primitives can be used for automatic processing. Semantic technologies embedded into OMM guarantee interoperability of the product memory during the complete lifecycle of smart objects and enable ubiquitous end-user access to the smart object's lifelog.

SEMPROM's layered architecture essentially virtualizes semantic product memories so that multiple physical realizations of their identification, computing, sensing, actuating and communication capabilities can be used at the same time for interacting elements of the Internet of Things. This means that our SEMPROM technology can be combined with a wide range of labeling and hardware options from simple bar code, QR codes and RFID tagging up to complex embedded devices like wireless motes, ultra-compact embedded system-on-module components with Ethernet and embedded Linux support, or other leading-edge microsystems for wireless M2M applications.

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[1] For the final report see www.w3.org/2005/Incubator/omm/XGR-omm-20111026/.

Although a key feature of a digital product memory is that it can capture the complete lifecycle of a product, for a given application only a specific phase of its life may be relevant, so that we can talk about a digital transport memory (Ulrich et al. 2013) or a digital maintenance memory as specialized versions of the more general notion introduced in SEMPROM (Fig. 2). Other subclasses of digital product memories are restricted to a certain field of industry like automotive, household appliances or pharmacy, so that domain-specific memory representations can be used.

These restricted approaches have the disadvantage that they don't scale up to the end-user or general lifecycle phases like recycling, since the end user will be unable or unwilling to access many different memory formats using a variety of propriety software packages for his car, his dishwasher, and his medications. Finally, there are subclasses of digital product memories that in contrast to SEMPROM are based on a single hardware platform like RFIDs.

The project RAN (**R**FID-based **A**utomotive **N**etwork) funded by the German Federal Ministry for Economics and Technology (BMWi) is an example of such a limited approach. The objective of this project is to increase information transparency within networks of production and logistics of the automotive industry applying RFID (Scholz-Reiter et al. 2011). Compared to SEMPROM, the RAN approach has a threefold restriction: it covers only one type of industry (automotive) and only two phases of the product lifecycle (production and logistics) and is based only on a single hardware platform (RFID).

3 Simple Forerunners of Product Memories Without an Internal Storage

One of the driving forces behind the introduction of digital product memories that goes beyond efficiency gains in production and logistics is the increasing demand for transparency by consumers who insist on sustainable production and agriculture. As stated in a US newspaper article, tracking can even become a consumer obsession: "America is becoming a nation of *track-a-holics*. We want to go online and track the whereabouts of everything we order—or do. It's sometimes because we need to know, but often it's simply because we want to know … Customers want some sense of control" (Bruce Horovitz in USA Today, 27 July 2009).

Already since 2008 the Iglo company marks each package of their cream spinach with a single individual code and the manufacturing time. Iglo offers a web portal to their customers that shows a multimedia presentation linked to the code on the product about the farmer family and their fields, where the spinach in the labeled frozen cardboard package was harvested (Fig. 5). This is a very simple example of traceability and combines increased quality assurance with extended customer information.

Domino's Pizza tracker is a similar example, since it uses simply the phone number of the customer to track the complete production and delivery cycle. It presents time-stamped information about the name of the employee preparing the pizza that

Fig. 5 Food transparency: tracking cream spinach and pizza

was ordered online, when it starts baking in the oven, when it is ready and packed for delivery and who will deliver it to the home of the customer (Fig. 5). This complete and personalized real-time process information is appreciated by customers waiting for their order. Recently iPhone and Android apps have been launched that help to order and track the pizzas even on mobile devices.

However, the tracking information is not based on real-time sensing of processing steps, but on input by various human operators, for example by pushing a button when the assembled pizza slides down the line to the pizza oven. When the delivery person grabs the order and puts it into a hot bag, they push again a button updating the tracker to indicate that the pizza is on its way. Because the company has the policy to deliver pizzas only within 9 minutes of the store in any direction, the tracker automatically updates to say that the pizza is delivered ten minutes after the button has been pressed. Of course, this information is quite unreliable, since there is no way to change what the tracker says in terms of delivery time based on variables such as traffic, accidents, red lights, and bad weather. Once the driver has left the store, the tracker will say that the pizza is delivered ten minutes later whether it has been or not. Some customers complained that the pizza tracker might be fake, when it turned out in their case that the information provided by the system was incorrect.

This shows that a digital product memory can be accurate only if it has its own sensing capabilities. Since the described precursors of product memories for the Iglo cream spinach or Domino's pizza had only an indirect, human-mediated link to reality they may report flawed information to the end-user. For example, freezer burn with ice crystals on the spinach, caused by too much temperature variation during transport or storage, may annoy the customer, or the pizza may arrive much too late. Thus, trusted transparency solutions for consumers must rely on full-fledged digital product memories as developed in our SEMPROM project.

4 Benefits and Risks of Semantic Product Memories

Semantic product memories have many benefits for producers as well as for consumers that go beyond increased product transparency, security and quality assurance discussed in the previous section (Fig. 6). Item-level anticounterfeiting solutions for protecting brands and customers are a clear benefit of embedded semantic product memories. With the help of semantic product memories, the ecological footprint can be monitored at an item level for compliance with government regulations and for increased consumer awareness. With a smartphone's NFC capabilities the semantic product memory can be accessed anywhere, so that useful maintenance help becomes available for the product owner or a professional repairman directly through the product itself. Reverse logistics and recycling efficiency can be improved significantly by semantic product memories, since disassembly and sorting information of products made from mixed materials can be made available.

Collecting and making information available—for example about a product's material mix, production history, location, movements, physical condition, and usage history—can help to improve its manufacturing, logistics and business processes and create new ones (Fig. 6). Existing business processes may become more accurate since real-time information taken directly from the point of action can be used to manage and optimize processes and related decision-making procedures. This may even lead to the distribution of existing business processes to the 'network edges' and can overcome many limitations of existing centralized approaches.

Moves to integrate semantic product memories into packaging, or better into the products themselves, will allow for significant efficiency gains in supply chain management. In addition, cost-efficient mass customization is enabled by semantic product memories, since a workpiece can navigate itself to the appropriate manufacturing services in a smart factory, so that unique products can be produced in a decentralized control paradigm (see Sect. 5). The information about the size, texture, color, material, geometry and optimal grip and lifting points stored in the product memory can be read by a robot's manipulators using integrated readers (Lemburg et al. 2013), to enable the robotic handling of complex workpieces and smart products with less sensing effort in an efficient way. Intelligent process mining becomes possible using a crowdsourcing approach generalized to smart objects, so that real-time and on-the-fly process optimization is enabled by semantic product memories.

Extended consumer information becomes available, since buyers of smart products can explore the complete episodic memory of a product in a multimodal fashion (Fig. 6). Tangible interaction with a product can be augmented by multimodal dialogs that are based on its object memory. A role-based access control mechanism

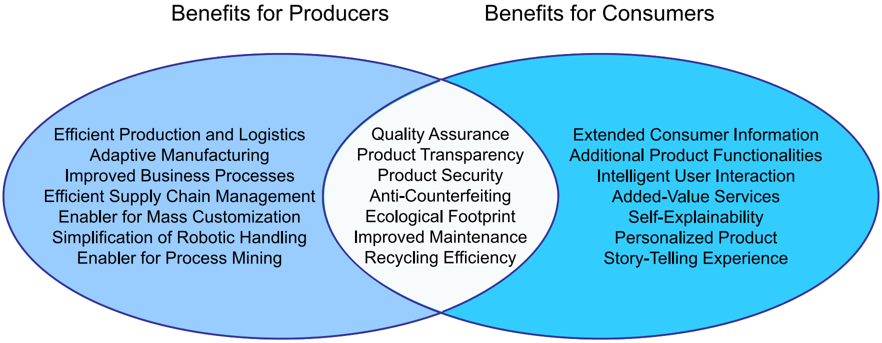


Fig. 6 Benefits of semantic product memories

ensures privacy and security of the semantic product memories. Added-value services like active product hazard warnings, or downloadable apps for adding new product functionalities based on the product's history and current context are enabled by semantic product memories. New customer experiences can be created through semantic product memories. The personalized product can explain its functions and tell the story of its life, so that artifacts can display anthropomorphic behavior.

But like with any new technology there are also various risks involved in the use of semantic product memories that are typical for innovative IT solutions:

- Privacy threats caused by interaction with labeled objects
- Unauthorized access, manipulation and misuse of the product memory
- Malware and denial-of-service attacks on product memories
- Backdoors in semantic product memories
- Unintended behavior and malfunction due to hardware and software bugs
- Physical destruction or theft of the product memory

However, in summary, the benefits of semantic product memories by far outweigh their risks.

5 Industry 4.0: The Role of Semantic Product Memories in Cyber-Physical Production Systems

During the past five years, it has become clear that digital product memories are a key driver of the fourth industrial revolution. Cyber-physical systems and the Internet of Things lead to a disruptive change in the production architecture: the workpiece navigates through a highly instrumented smart factory and tries to find the production services that it needs in order to meet its individual product specifications stored on the product memory. In contrast to the classical centralized production planning and manufacturing execution systems, this leads to a decentralized production logic, where the emerging product with its object memory is not only a central information container, but also an observer, a negotiator and an agent in the production process. Such Cyber-Physical Production Systems (CPPS) are based on M2M and All-IP wireless communication between factory components (Zühlke 2010).

The future project Industry 4.0 is setting the stage for the smart factories of the future and is an integral part of the high-tech strategy of the German government. The sensor-based, networked smart factories developed in the Industry 4.0 program are well-suited for high-precision, superior quality production of high-mix and low-volume smart products. They enable clean, resource-efficient and sustainable green production as well as urban production, so that smart factories could move back to the cities—ideally within walking distance of employees' homes.

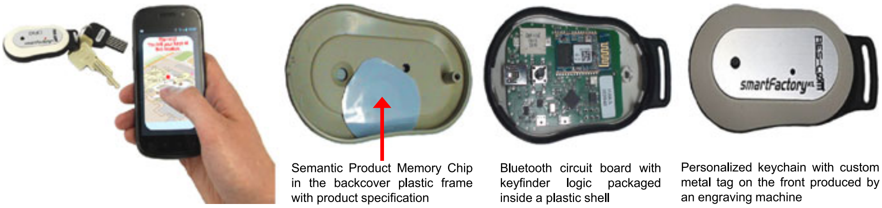
Cyber-physical production systems have to deal with the real-time demands of manufacturing, so reactive and fast proactive behavior of the active semantic product memory of machined parts is essential. Unfortunately, larger buffers for higher bandwidth in the web have caused an increased latency of Internet traffic. Thus, for Industry 4.0 we must rely on the immediately accessible locally stored contents of digital product memories inside the machined parts and cannot wait for information retrieved from memory extensions stored in a data cloud.

While SEMPROM focused on *passive* semantic product memories, in our current RES-COM project (**RES**ource Conservation by Context-activated M2M **COM**munication) we extend this notion to *active semantic* product memories that not only monitor resource consumption, but also trigger coordinated actions to increase resource efficiency by machine-to-machine communication (Kröner and Schlick 2010) in our *SmartFactory*$^{\mathbf{KL}}$. For example, in RES-COM the active semantic product memory of a workpiece of an assembly line for low-volume production may specify that this particular unfinished product must be completely assembled within the shortest possible timeframe, since a premium customer of the smart factory needs the finished product as soon as possible.

Using M2M communication of the active semantic product memory with a workpiece carrier that also has its own active semantic product memory and with alternative assembly components, the workpiece is advanced faster along the production line and assembled by faster, but more energy-intensive tools than regular workpieces. Thus, the prioritized workpiece actively selects among alternative assembly stations (e.g., a faster but energy-intensive pneumatic assembly tool vs. a slower, but energy-efficient electric assembly tool) realizing a decentralized control scheme in the Internet of Things. In RES-COM, the overall energy consumption for the production of an individual item can be computed from the data stored in the relevant product memories and visualized on a mobile tablet of a production engineer (Fig. 7). The massive amount of active product memories in a smart factory generates an enormously big data stream that can be harvested and analyzed for resource-efficient and high-quality production.

As a first example of a service-oriented architecture of a CPPS (Loskyll et al. 2011) with active semantic product memories we have developed a production line for individualized smart keyfinders in DFKI's *SmartFactory*$^{\mathbf{KL}}$ in the framework of

Fig. 7 Mobile visualization of semantic product memory contents in RES-COM



Semantic Product Memory Chip in the backcover plastic frame with product specification

Bluetooth circuit board with keyfinder logic packaged inside a plastic shell

Personalized keychain with custom metal tag on the front produced by an engraving machine

Fig. 8 The smart keyfinder with its semantic product memory chip

the RES-COM project. The product specification is stored on the memory chip inside the backcover plastic frame (Fig. 8). Using Bluetooth technology, the keyfinder will alert its owner anytime his keys are more than 30 feet away from his smartphone. The smart keyfinder is itself a simple example of a cyber-physical system that is produced by a complex cyber-physical production system.

Key elements of the decentralized CPPS control system are service discovery and matchmaking processes (Blake et al. 2012) between a given production service request of an emerging product and a particular production service of one of the machines that is registered with the semantic matchmaker of a smart factory (Fig. 9). The service matchmaker will return a ranked list of relevant and available services offered to a workpiece in its current production environment. Semantic service descriptions stored in OMM can be used to actively negotiate between service providers and service seekers to find the optimal match for a set of given production and resource constraints.

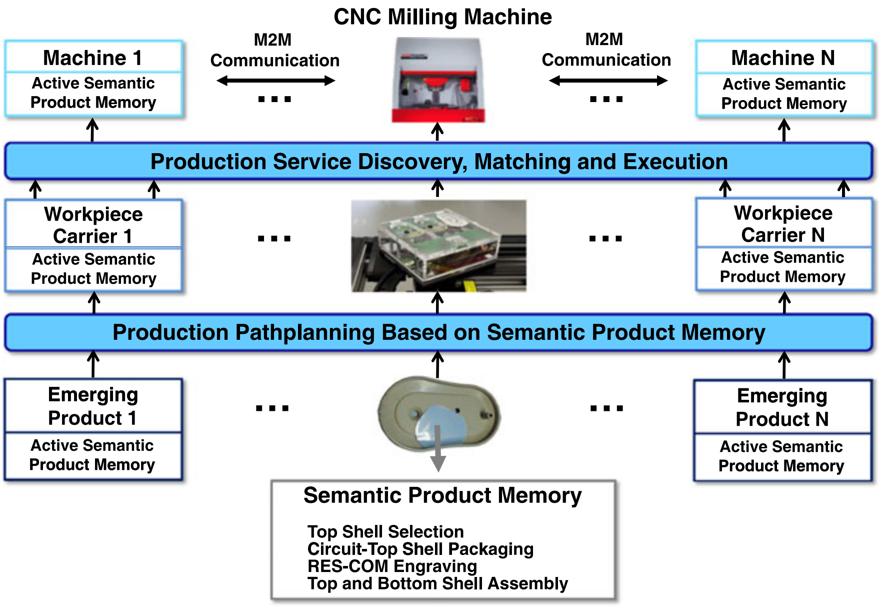


Fig. 9 Key components of a service-oriented cyber-physical production systems

The CPPS for the smart keyfinder is a use case of the RES-COM system as one of the first projects in the Industry 4.0 initiative. RES-COM was launched in July 2011 and is funded by the Department for IT Systems of the German Federal Ministry of Education and Research (BMBF) for a period of three years with about 9 million €.

Active semantic product memories play a role on three levels of the CPPS: in the emerging products, in the workpiece carriers, and in the various machines of the smart factory (Fig. 9). The workpiece carrier in the current configuration can transport up to three workpieces for keyfinder products (see photo in the center of Fig. 9). The semantic product memory contains individual production requests, like the engravature of the string "RES-COM" on the metal tag on the front of the keychain (Fig. 8). In this case a CNC milling machine is found that can carry out this service. Then the active semantic memory of the workpiece carrier makes sure that the workpiece travels to the robotic arm that feeds the milling machine. Detailed information about each successful production step can be stored in the emerging product's memory.

In the near future automatic service composition algorithms may be implemented in CPPS, so that given a repository of service descriptions of machines in the factory, and a query from an active semantic product memory of a workpiece with requirements of the requested service, in case a matching service is not found, the semantic service composition engine will find a set of services that can be combined to obtain the desired service.