Digitalization from an architectural perspective

A cross-industry reference architecture with a focus on the Internet of Things, cognitive computing, and augmented reality

CONTENT

Digitalization entails convergence

The European Commission (2013) explains **convergence** with the following definition:

"Convergence can be understood as the progressive merger of traditional broadcast services and the internet. This results in viewing possibilities extending from TV sets with added internet connectivity, through set-top boxes delivering video content "over-the-top" (OTT) to audiovisual media services provided via PCs, laptops, or tablets, and other mobile devices. Consumers use tablets or smartphones while simultaneously watching TV, for instance to find out more about what they are watching or to interact with friends or with the TV program itself."

At BusinessDictionary.com (2016), the fundamental definition of **digitalization** is the "integration of digital technologies into everyday life by the digitization of everything that can be digitized."

This definition has been extended and used in various contexts. The dictionary of IGI Global (2016) adds "the literal meaning of digitalization gives an apparent idea of development and technology-dependent world" and Gartner (2016) concretizes in its glossary that "digitalization is the use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business."

Storsuhl and Stuedahl (2007) consider convergence from two perspectives: first, they consider what is converging, such as networks, terminals, or social practices; and second, they analyze what happens when something converges, such as merging information from different ubiquitous event sources and combining processes across different systems and devices that "come together" such as the cell phone, television, and personal computer. The fusion of these connections, which themselves generate new complexities, can be thought of as the mirror of digitalization. Both digitalization and convergence mutually condition each other. On the one hand, digitalization is an enabler of convergence since, as per Storsuhl and Stuedahl (2007), it "contributes to the blurring of boundaries between different media" by making the signals themselves equal, regardless of what kind of information or communication they represent. On the other hand, digitalization is conversely reinforced by convergence due to the retroactive effect of increasing the digitalization requirements that originate from the convergence itself. This improves usage of collected data and information while providing promising insight into customer behavior.

Organizations benefit from this convergence because the dramatic reduction of media breaks leads to continuity. Convergence ensures that individual processes are smoothly connected without delay or disruption. Since data is available and traceable at any process stage, convergence also improves the transparency, analyzability, and usability of the collected data. The new data analysis capabilities enable organizations to add value for themselves and their customers. In this context, three digital technologies are at the forefront: the **Internet of Things** (IoT), **cognitive computing** (CC), and **augmented reality** (AR). IoT senses and ingests data automatically within processes and across organizational boundaries. Cognitive computing enables intelligent and seamless interaction between humans and systems or devices using data obtained by IoT. Augmented reality helps to visualize and utilize these data and provides an interface between the digital and real worlds.

Defining a cross-industry reference architecture

This point of view explains digitalization from an architectural perspective. We focus on three concepts that each play an essential role in the digital world:

- Internet of Things (IoT)
- Cognitive computing (CC)
- Augmented reality (AR).

These concepts lead us to three architectural viewpoints. After a short overview of the three concepts, we will transform them into building blocks within a cross-industry digitalization **reference architecture**.

IoT, CC, AR: three architectural viewpoints

Internet of Things (IoT) enables the digitization of our society and economy. Objects and people, each with their own unique identifiers, are interconnected through wireless ad hoc networks such as Bluetooth, Zigbee, or Z-Wafe and they report on their status and the surrounding environment (European Commission, 2016). According to a recent European Commission study by Aguzzi et al. (2014), the market value of the IoT in the EU is expected to exceed one trillion euros in 2020.

Cognitive computing derives intelligence and knowledge from huge volumes of data, allowing it to enable IT systems to make real-time decisions. It relies on new approaches, such as brain-inspired neuromorphic computing and memcomputing, that are key to non-von Neumann architectures in which memory and logic coexist rather than having both units separated (CORDIS, 2016). Cognitive computing thrives on the available and ubiquitous data generated by digitization, making it a driver of digitalization itself.

Augmented reality is a concept to increase the user's perception of, and interaction with, the real world by placing virtual objects into a scene that simultaneously appear in the same space of the real world. According to Azuma et al. (2001), an AR system possesses three main characteristics. It:

- combines real and virtual objects in a real environment
- runs interactively, and in real time
- registers (aligns) real and virtual objects with each other.

Augmented reality allows users to benefit from data gathered using digitalization and cognitive computing.

Specifying the dimensions and frame of the reference architecture

The first dimension: architecture domains

We will distinguish, in accordance with TOGAF® (The Open Group Architecture Framework), four essential architecture domains:

- **Business architecture**
  spans from business capabilities and processes to strategic elements.
- **Data architecture**
  encompasses the data mode, its data, entities, business objects, and relationships.
- **Application architecture**
  reflects the application landscape. This includes the interfaces and the interactions between the deployed software solutions.
- **Technology architecture**
  contains the elements for the establishment and operation of the IT infrastructure and forms the basis on which applications are procured, integrated, and hosted.

The second dimension: stages of digitalization

Digitalization is horizontally divisible into four sequentially arranged domains that can be understood as the stages of digitalization:

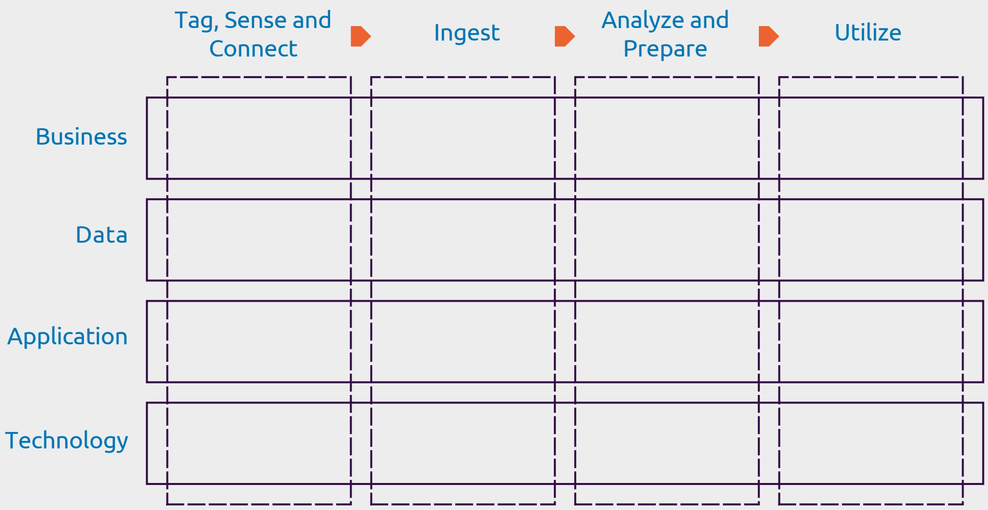
1. Domain: tag, sense and connect
Objects are tagged with a unique ID such as Datamatrix or RFID to identify, locate, track, and measure movement, gestures, and even analyze the environmental properties of these objects. As this includes interconnecting, objects may be able to recognize each other and interact through wireless ad hoc networks.

2. Domain: ingest
All information captured by sensors is ingested into a central store that is usually capable of absorbing large quantities of data.

3. Domain: analyze and prepare
This step includes the analytical processing of the captured data in preparation for the fourth step.

4. Domain: utilize
Value is generated by commercializing and utilizing the insights gained from the analyzed and processed data. This fundamental relationship is depicted in figure 1.

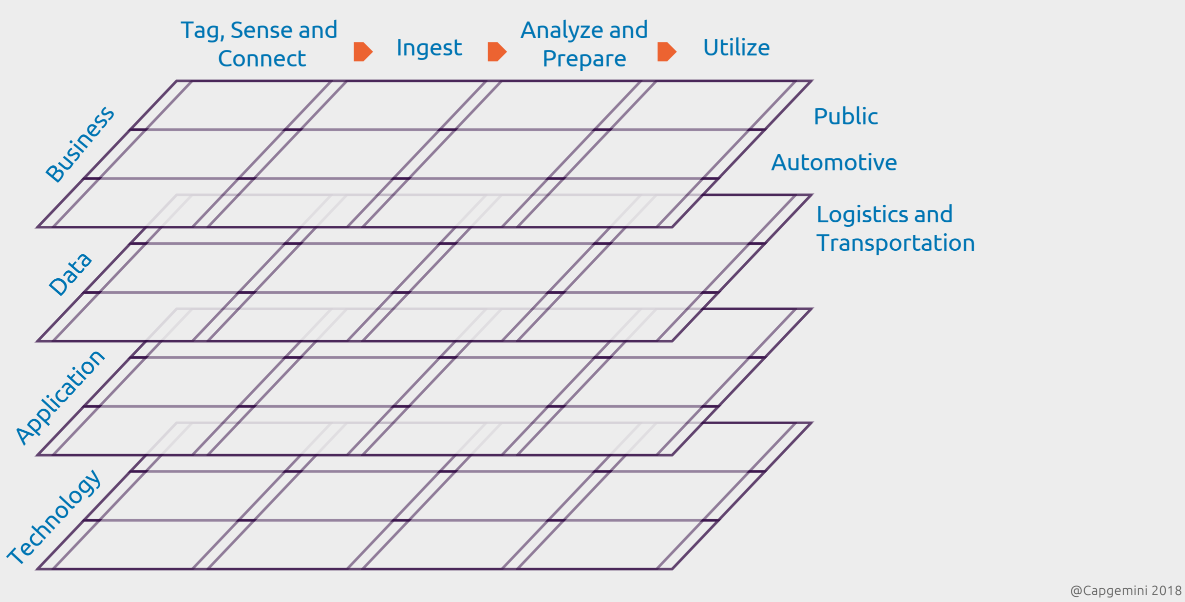
Figure 1: Fundamental frame (vertical slice) of the digitalization reference architecture.



The third dimension: industries

Technology components can be used across different industries. Applications that are developed and run in different industries can both interact with each other and exchange data through these industry-specific applications. These relationships can exist and be used on a business level, resulting in organizational boundaries intersecting between different industries. For this reason, the frame of the digitalization reference architecture needs a third dimension: industries. Certain building blocks can be positioned within the horizontal planes that are shown in figure 2, for example public, automotive and logistics, and transportation.

Figure 2: Horizontal slices of the digitalization reference architecture.



Filling the digitalization reference architecture with building blocks

Once the digitalization reference architecture frame has been constructed, the next step is to define the specific building blocks that fit into it. By applying the principle of "divide and conquer," we can focus on the triple threat of IoT, CC, and AR as a unified entity.

Internet of Things

Figure 3 illustrates IoT-focused building blocks within a digitalization reference architecture frame. Building blocks for **technology architecture** are AutoID, such as RFID or data matrix, and include sensor components within the tag, sense and connect domain. Cellular and ad hoc networks cover the ingest domain, since data is transmitted between wirelessly connected objects or actuators - the "things" - in an IoT network. At least one object within this network is responsible for ingesting data. Cloud solutions, such as Azure IoT, AWS IoT, Blumix, and others, provide channels into which data can be ingested, processed, analyzed, and prepared for later provisioning in various use cases.

IoT application platforms are a part of application architecture. They cover the four previously outlined domains of tag, sense and connect, ingest, analyze and prepare, and utilize. These four domains correspond to Maniappan's (2015) value chain, which consists of three blocks:

- things and devices
- communication through network infrastructure
- computing and storage, the final stage of which incorporates fast and big data analytics for use by enterprise applications.

Large players within this chain include Thingworx, Connext Data Distribution Service (DDS), ThingSpace, and OpenSensors. DDS represents an Object Management standard (OMG, 2015) to which IoT solutions should comply in order to foster interoperability, open architecture, and decreased lifecycle costs.

It should be noted that solutions - be they cloud solutions as part of the technology architecture or IoT app platforms belonging to application architecture - may cover cognitive computing or augmented reality capabilities as well. The boundaries between these three priorities are blurred, especially on a solution level.

Consider Vuforia, a leading software development kit. It was acquired by ThingWorx in November of 2015 and now, ThingWorx Studio can combine Vuforia's AR functionality with their own IoT platform. Another example is IBM's Watson, which has its own IoT capabilities known as Watson IoT.

Data Architecture designates data collected from sensors. OpenSensors, a central hub for publishing and subscribing events (in accordance with the pub/sub pattern) to sensor data streams, uses the MQ Telemetry Transport (MQTT) protocol. Finley (2014) describes the OpenSensors platform as a sort of social network for the world's online sensors. This platform centrally implements the open data idea of cultivating a huge repository of accessible information originating from environmental sensors, web-connected cars, fitness trackers, or home automation systems. Additionally, private data streams that can be accessed through paid services are supported.

The **business architecture** comprises building blocks that include beneficial applications of IoT: digitally labeled objects, interconnected sensors, and sensor-captured, and real-time analyzed data coupled with alerts. An increasingly important building block for industrial enterprises is maintenance which, accompanied by condition monitoring, can be remotely completed and performed in a predictive and prescriptive way.

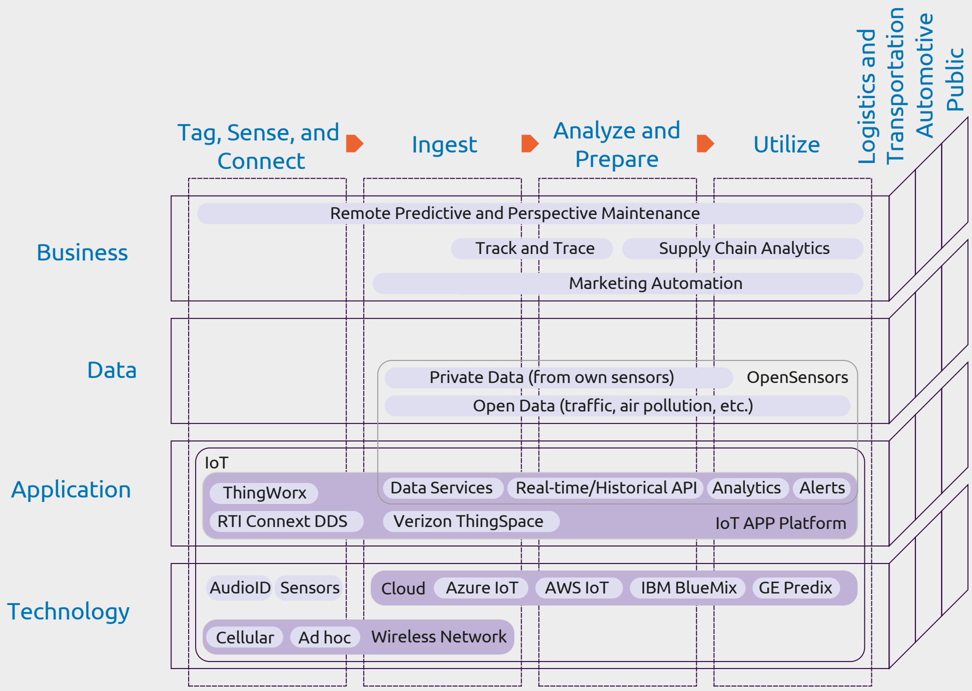
Concrete business cases for **remote diagnostics**, **supervision**, and **maintenance** can be found in offshore turbines. These are "increasingly being installed in locations characterized by extreme climates so that they can exploit their high wind energy potential on high mountain peaks, far offshore, or standing in snowbound desolation" (Kreutzer 2014). Remote maintenance, powered by comprehensive and detailed data, eliminates service calls and allows wind turbine units to continue operating at optimum performance levels.

Track and trace is another business case that is highly relevant in the pharmaceutical industry. On the one hand, counterfeit medicines pose a growing threat; on the other hand, all medicines require a high level of quality assurance for manufacturing, transport, storage, and administration. Accordingly, safety in the context of both materials management and supply management is crucial for protecting patients. 2001/83/EC and Regulation (EC) No 726/2004 specify track-and-trace capabilities for medications that must be implemented by 2017. Accordingly, drug packages must be serialized with a data matrix code or RFID label. The RFID-based model, however, involves interaction between the manufacturer, wholesaler, pharmacy, and physician. Supply chain analytics-to continue with this example-allows for the detection of irregularities, such as large-quantity purchases that never appear on the market. These "black holes" may be linked to illegal exports, counterfeiting, and product manipulation.

A business case for consumer context is data-driven **marketing automation**, which improves customer experience by analyzing buying habits in order to properly target point-of-sale (POS) notifications and supply advertisement that perfectly align with customers' interests, behaviors, and past purchases. One example can be found in Leung's (2014) comments about smart homes and lightbulbs. Not only could the home identify the need to replace a light bulb, it could also send a digital coupon for a new bulb directly to the homeowner's cell phone. The exact number of hours of the light bulb's usage can be recorded and transmitted in order to notify the customer when the light bulb is approaching the end of its life.

The European Commission launched an initiative for IoT platform development called the IoT-European Platforms Initiative (IoT-EPI) to "build a vibrant and sustainable IoT ecosystem in Europe, maximizing the opportunities for platform development, interoperability, and information sharing." Strategic IoT areas include smart agriculture, smart cities, smart industries, sustainable reverse logistics, smart water management, and smart grids. Furthermore, the Industrial Internet Consortium (IIC) published a standard called the Industrial Internet Reference Architecture (IIRA), which defines the industrial internet as an "internet of things, machines, computers, and people, enabling intelligent industrial operations using advanced data analytics for transformational business outcomes," which "embodies the convergence of the global industrial ecosystem, advanced computing and manufacturing, pervasive sensing, and ubiquitous network connectivity" (Industrial Internet Consortium, 2015). This standard consists of a unified framework that integrates existing and emerging standards into a common structure for efficient industrial IoT development, enabling engineers to quickly and easily connect, scale, and detect interoperability gaps between IoT components.

Figure 3: Placement of IoT building blocks into the digitalization reference architecture.



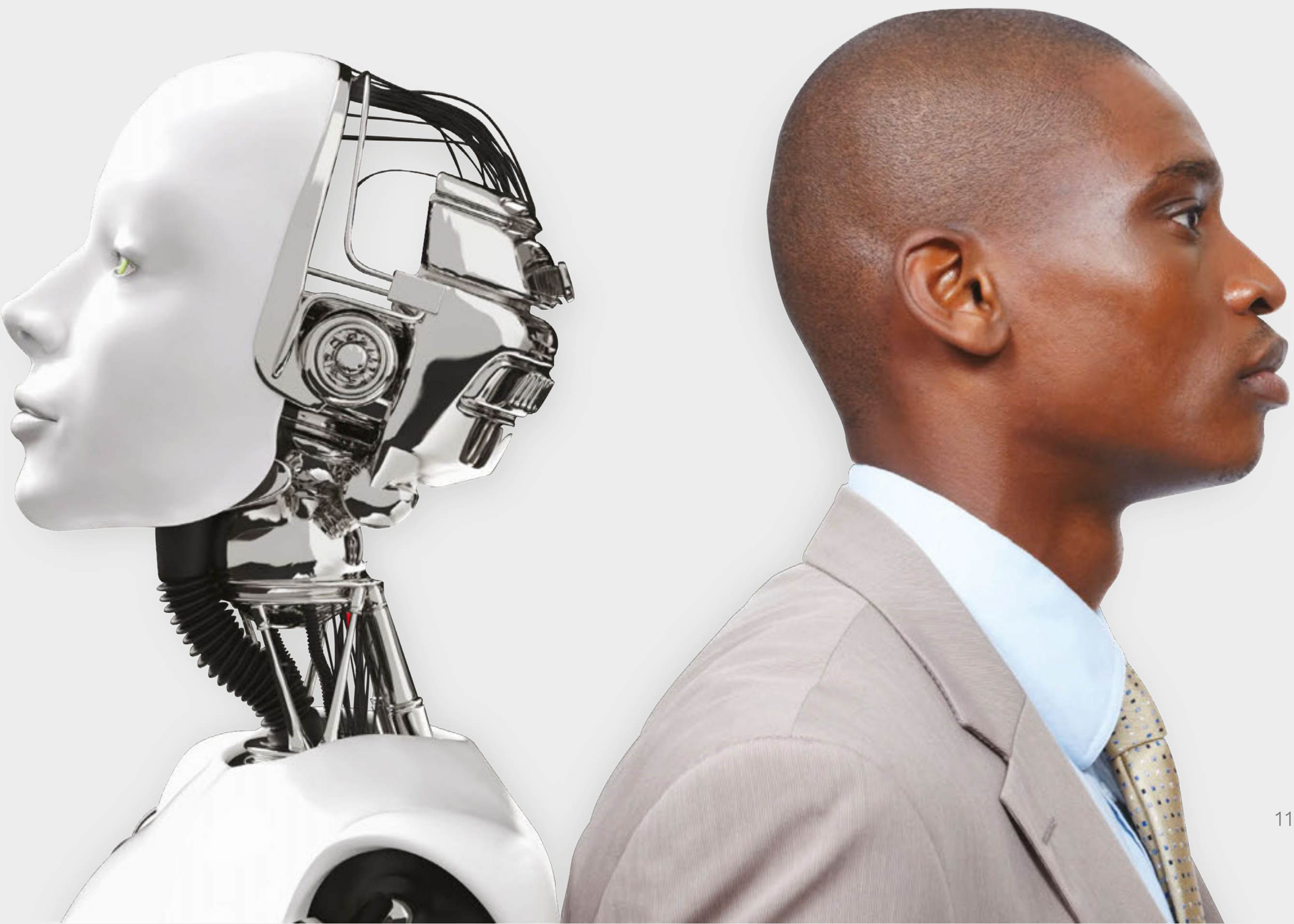
Cognitive computing

In figure 4, the building blocks focusing on CC are placed into the frame of our digitalization reference architecture. Cognitive computing platforms cover the **technology architecture** and application architecture. Within the technology architecture, interfaces with IoT components are located in the tag, sense and connect domain. These components - connected actuators such as people, sensors, devices, and "things" in the sense of "Internet of Things"- stream data to the CC platform, which then ingests this data through signal or data miner and processes it. This can precipitate an action in reverse on those very "things" from which the data was collected in the first place. The combination of computing's movement into the physical world through IoT with cognition - or in other words, thinking - capabilities by CC is called "cognitive IoT" (Matthews, 2016).

The conceptual basis for CC is machine learning, a subfield under the artificial intelligence (AI) umbrella, which "refers to a wide variety of algorithms and methodologies that enable software to improve its performance over time as it obtains more data" (Noyes, 2016). Machine learning incorporates a set of techniques that allows a computer to learn and manifest cognition or intelligence. Noyes cites that machine learning is through "programming by input-output examples rather than by coding" and specifies that machine learning incorporates neural networks, decision trees, Bayesian belief networks (modeling reality with probabilities), case-based reasoning, instance-based learning, and regression techniques. Machine learning includes data analysis disciplines that range from predictive analytics and data mining to pattern recognition (Garcia, 2014).

Mining the input within the ingest domain comprises natural language text and speech, audio, visual input-like gestures or facial expressions, and haptic (touch-based) inputs. All this input is processed and subjected to pattern recognition within the domains of "analyze," "prepare," and "utilize." Technological building blocks such as signal, image, speech, and natural language processors, along with components for object and pattern recognition, anomaly detection, and motion analysis are used for this purpose.

The **application architecture** comprises building blocks that deliver a concrete CC function users benefit from, such as a natural language interface, a sentiment and emotion recognizer, and other machine-learning functions. A natural language classifier interprets the intent behind the text, which may have been collected by a natural language interface, and returns a corresponding class with associated confidence levels (see data architecture). For example, text message or email texts can be classified as personal, work, or promotional. A user modeler understands personality insights and demonstrates deeper understanding of a user's personality characteristics, needs, and values.



In short, it provides the basis for capabilities such as personal recommendations within the business architecture. The bandwidth of application-specific building blocks also leans toward IoT. This involves geo-spatial functions such as map matching (including the exact location of a car on a mapped road) and searching for the shortest route based on the worldwide road network. Furthermore, insight into the driver's behavior can be derived on the basis of car probe data. This may include speeding, frequent or harsh acceleration and braking, and sharp turns.

Data architecture within the ingest domain includes user data and input that may originate from various sources, including email, mobile applications, social media, transactions, documents, search requests, or operational technology (OT) components integrated with IT. Environmental data is also located in the ingest domain. Pre-trained models are used within the analyze-and-prepare domain. The output data of a CC analysis function contains classes (as result of content classification), sentiments, and emotions.

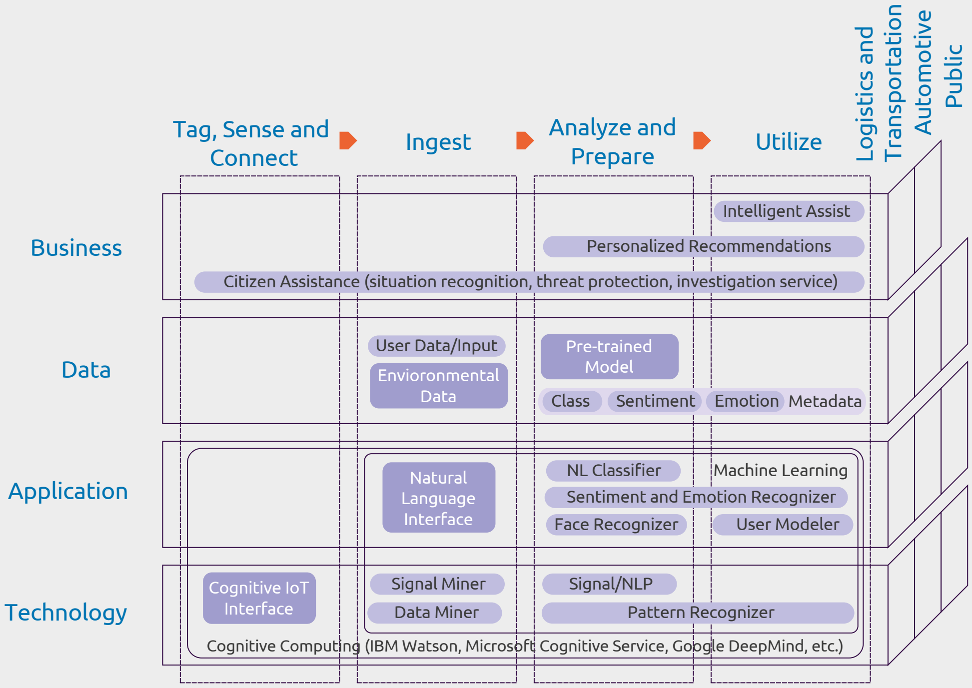
Smart data results in the creation of outcome based on the analysis of data drawn from heterogeneous sources. It hails from the content analytics and insights used to optimize decision-making. In short, smart data builds on the principle that data produced through digitalization can be treated as raw material for economic value generation, innovation, and growth.

Capabilities within **business architecture** are backed by the building blocks of other underlying architectures like data, application, and technology. One use this architecture surfaces in the form of an artificially intelligent attorney: 80% of people in need of legal advice cannot afford a good lawyer (Miller 2015). Another application hails from the need for wealth management and investment assistance, as these capabilities can offer tradeoff analysis that balances outlined, weighted criteria such as profit expectation, risk, and cost.

Personalized recommendations that employ intelligent commerce may provide real-time, context-based, and consumer-oriented product suggestions derived from a customer's unique attributes, past purchases, and buying behavior. A "cognitive rules advisor" (termed by IBM) employs machine-learning techniques to learn, advise, and suggest the offers and messages that could be shared with buyers. The main objective of personalized recommendations consists in enabling marketers to provide customers with the most relevant and personalized offers in realtime. This CC capability melds well with the IoT building block of marketing automation (see figure 3).

Citizen assistance comprises capabilities derived from permanent access to ubiquitous data and information of connected "things" that are evaluated, analyzed, and checked against (local or worldwide) investigation queries, search, and valuation criteria in real time. A parked car, for instance, can identify and automatically report a missing pet based on the pet's chip. This capability also applies for any digitally perceptible item that might be reported stolen or lost. Additional CC capabilities range across medical research (e.g., finding appropriate cancer treatments), fraud prevention and digital forensics for crime detection, and sentiment analytics to take a crowd's temperature on a brand or a product. A supplementary spectrum of real-world applications for cognitive computing is provided in Lamont (2015). One example is ENGAGE for Healthcare from CognitiveScale, which provides care, an application that provides services and support to individuals and care managers with chronic conditions and diseases in both clinical and non-clinical settings. Another example is the CaféWell Health Optimization Platform from Welltok.

Figure 4: Placement of building blocks into the digitalization reference architecture that are focused on CC.



Augmented reality

Figure 5 shows the AR building blocks that are positioned in our digitalization reference architecture. The domain tag, sense and connect of the **technology architecture** distinguishes between marker-based and markerless AR. In the first case, cameras and visual markers - usually black and white markers (square images) - are involved. These markers are provided beforehand and the application knows exactly what should be recognized while acquiring camera data. In the second case, an object of any type (picture, human body, head, eyes) is recognized without markers.

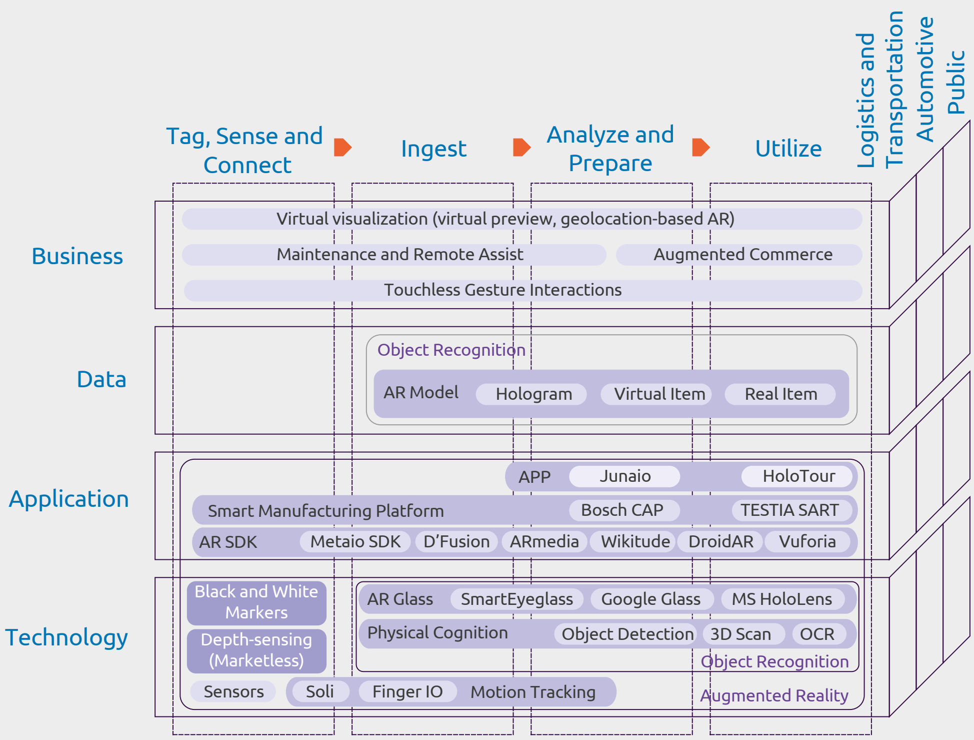
Hardware can also be located within the technology architecture. This includes sensors, augmented reality glasses such as SmartEyeglass, Google Glass and HoloLens, and FingerIO devices. Latter devices are miniaturized sensors that track motions and are an underlying technology for touchless gesture-interaction-incorporating radar (in the case of Soli) or active sonar (in the case of FingerIO). Along with the AR glasses, object recognition includes capabilities for physical cognition, especially object detection, 3D scan, and optical character recognition (OCR).

Application architecture partly consists of augmented reality software development kits (SDKs) such as Vuforia, which PTC acquired from Qualcomm, or Metaio, which now belongs to Apple. Smart manufacturing platforms are based on the SDK (as a further layer) SDKs and usually cover more than one industry. In order to integrate machines and manufacturing devices, these platforms must provide SDK functionality. Strong players are Bosch's Common Augmented Reality Platform (CAP) and the TESTIA Smart Augmented Reality Tool (SART).

Data architecture includes holograms, the models of virtual and real items and their relationship to one another. Holograms are not only confined to 3D models, but also comprise meta-information and links to other virtual or real items. In a construction industry-specific data architecture for example, data gathered by smart helmets that contains information about the worker's surroundings may be collected. For this purpose, IoT comes into play by enabling "things" - a helmet in the current example - to capture, transmit data, and communicate with other components. Beyond this example, Newman (2016) provides other cases on how the "marriage of AR and IoT" is "revolutionizing the way we do business."

Business architecture encompasses the capabilities of virtual visualization, including virtual preview and geolocation-based AR, maintenance and remote assist, augmented commerce, and touchless gesture interactions. Probably the most well-known business case for geolocation-based AR that met with unmistakable global success is the mobile application Pokémon GO. It not only excelled in the entertainment industry, but also in education, and the automotive industry, providing relevant cases for **geolocation-based AR**. Along the same lines, Delić, Domančić, Vujević, Drljević, and Botički (2014) introduced a geolocation-based augmented reality application for vocational geodesy education. The global tire manufacturer Continental makes the case for an augmented reality heads-up display (AR-HuD), which displays all relevant information including speed, important warning messages, and tips for navigation directly in the field of view. By enriching the actual driving environment, a change originally conceived as an ergonomic display, a new interaction concept emerges that supports the driver in situational and location-based ways.

Figure 5: Augmented reality building blocks within the digitalization reference architecture.



Another significant building block is **maintenance and remote assist**, which represents the concept of using AR for maintenance jobs. Henderson and Feiner (2007) investigate increasing maintenance personnel productivity through AR in their research on augmented reality for maintenance and repair, which is funded in part by the Air Force Research Laboratory (AFRL) and supported by NVIDIA and Google. Similar research has been carried out by Fraunhofer IGD together with the German Aerospace Center (DLR) and Sidel S.p.A (Webel et al., 2011) and by the Bremen Institute for Production and Logistics with their project entitled "AR Maintenance System" that seeks to develop AR glasses to assist in performing services at wind energy installations (Nollmann, 2015). A third case is the solution based on HoloLens wearable holographic technology implemented by Trimble and Microsoft for architects, engineers, contractors, and owners (AEC-O) to improve quality, transparency, and collaboration across the design-build-operate lifecycle of buildings.

Augmented commerce allows customers to view products virtually in a real-world environment before they purchase them. Known applications are AR-based 3D interior design systems, where end users can integrate 3D product models (e.g., furniture) into a set of images of their real environment (CORDIS, 2005). Another example, Cimagine, provides an augmented reality platform for retailers, brands, and manufacturers that allows consumers to envision and interact with physical products virtually.

Touchless gesture interactions grant end users touchless control over devices through a universal set of gestures. Press an invisible button between thumb and index fingers by tapping two fingers together as shown in figure 6. The chip (motion tracking sensor) can be embedded in wearables, phones, computers, cars, and IoT devices in our environment. FingerIO, developed at the University of Washington with Microsoft Research (Nandakumar, Iyer, Tan, & Gollakota, 2016) as well as Google Soli, are real solutions that enable touchless gesture interactions.

Figure 6: Touchless interactions by virtual tool gestures (Google Soli).

Conclusion and Outlook

Digitalization opens a wide field of possibilities in relation to technology, and digitized or collected applications, and new utilizable data and business. The reference architecture structures outlined in this paper all relate to digitalization by demystifying three of its concepts: the Internet of Things, cognitive computing, and augmented reality. These concepts are categorized, positioned, and linked to each other within the vertical slices of the intersectional reference architecture that are not specific to a particular industry. Within each architecture domain - from business to technology - horizontal planes span a predefined set of industries and explain connections between the interplay of components that belong to a particular industry. The combination of the public, transportation, and automotive sectors in the horizontal planes demonstrates how different sectors can be interlinked.

For example, the transportation industry is connected with the public sector since information flows between public interfaces for traffic and road pricing, logistic, and fleet management systems. The public and automotive sectors are synergistically connected via the Vehicle-2-Grid (V2G). The energy, pharma, and automotive sectors may even become one horizontal plane when we think about V2G, Good Distribution Practice (GDP), track and trace, and cold chain monitoring. The reference architecture discussed is applicable for each industry. It standardizes the interfaces and processes between interlinked industries and makes the real world easier to understand. It simplifies the implementation of systems that enable seamless interaction.

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