Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet

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A worldwide movement in advanced manufacturing countries is seeking to reinvigorate (and revolutionize) the industrial and manufacturing core competencies with the use of the latest advances in information and communications technology. Visual computing plays an important role in this vision as an enabling technology for complete solutions.

There is a worldwide movement in some of the most advanced economies seeking to improve productivity and efficiency in industrial manufacturing by incorporating the latest advances in information and communications technology (ICT). This vision recognizes that the adoption of emerging ICT technologies, and their relative weight in the new competitive approaches to manufacturing will grow in the years to come and will open completely new solutions and services. National and regional governments are aware of the importance of ICT in industry, and for this reason, they are developing and launching novel initiatives and programs such as the Industrial Internet and the Advanced Manufacturing Partnership in United States, Industrie 4.0 in Germany, and La Nouvelle France Industrielle in France. Even smaller regions with a long tradition in manufacturing are following the trend from a local perspective (for example, the Basque Country intelligent specialization policy RIS3 in advanced manufacturing).

There are several technologies involved in this global trend such as the Internet of Things and Services, industrial automation, connectivity and ubiquitous information, cybersecurity, intelligent robotics, product life-cycle management, semantic technologies and industrial big data. Also, the technologies that comprise visual computing provide a valuable support for the new aforementioned initiatives and are considered, for example, in the German vision of Industrie 4.0.[1] (In this context, *visual computing* can be defined as the entire field of acquiring, analyzing, and synthesizing visual data by means of computers that provide relevant-to-the-field tools.) Industrie 4.0 in particular addresses several key aspects:

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- IT-enabled mass customization of manufactured products, in which production must adapt to short batches or even individual needs;
- automatic and flexible adaptation of the production chain to changing requirements;
- tracking and self-awareness of parts and products and their communication with machines and other products;
- improved human-machine interaction (HMI) paradigms, including coexistence with robots or radically new ways to interact and operate in factories;
- production optimization due to Internet of Things (IoT) enabled communication in smart factories; and
- radically new types of services and business models contributing to changing ways of interaction in the value chain.

As explained in a key reference document,[1] with the introduction of the Internet of Things and Services, cyber-physical systems (CPS) are central to the Industrie 4.0 vision. CPS include smart machines, storage systems, and production facilities that can exchange information with autonomy and intelligence, are able to decide and trigger actions, and can control each other independently.

To achieve this vision, it is necessary to capture, analyze, and interact with both the real (physical) and the virtual (digital/cyber) production worlds, with a high level of precision in all dimensions (spatial and temporal).[2] From this perspective, the application of computer graphics and computer vision (visual computing) technologies play an important role in achieving Industrie 4.0 solutions.

This article explains how visual computing technologies are key enablers for Industrie 4.0 and Industrial Internet. Specifically, we introduce a conceptualization of the main visual computing technologies for Industrie 4.0. Furthermore, we identify key technologies and challenges to be addressed by the scientific community to foster the realization of Industrie 4.0. Finally, we also show some concrete examples of applied research projects in international scenarios and their alignment with this vision.

Global Industrial Trends

Advanced manufacturing entails the rapid transfer of new knowledge into industrial processes and products.[3] ICT is a key enabling technology to accelerate and improve productivity in manufacturing. The deployment of ICT in the late 1960s into production was actually an industrial revolution. The competitive factories of today could not be conceived without the industrial automation pyramid (including programmable logic control, manufacturing execution systems, or enterprise resource planning) in production, or the product life-cycle management supported by advanced CAD/CAM/CAE tools.

Recent developments in ICT and the latest Internet-related technologies are opening up revolutionary possibilities for manufacturing and production. Due to several technical, market, and cultural reasons, however, the manufacturing industry is paradoxically one of the last niches to be conquered by the pervasive and ubiquitous developments associated with the Internet of Things and Services.

Recent developments in ICT and the latest Internet-related technologies are opening up revolutionary possibilities for manufacturing and production.

In the US, the so-called Industrial Internet—first introduced by General Electric in its visionary paper and considered the third wave of innovation after the industrial revolution[4]—is already widely accepted in many American organizations such as the National Science Foundation (NSF) Industry/University Cooperative Research Center (I/UCRC) for Intelligence Maintenance Systems (IMS) and other relevant industrial actors. This initiative has a strong focus on a higher degree of intelligence with the power of advanced computing, analytics, low-cost sensing, and new levels of Internet connectivity.[5] Three elements characterize this vision:

- intelligent machines,
- advanced analytics, and
- people at work.

The definition of the Industrial Internet data loop[4] includes five pillars, some of them directly related to visual computing: instrumented industrial machines, industrial data systems, big data analytics, remote and centralized visualization, and physical-human networks.

In Europe, the strategic initiative Industrie 4.0 (whose leitmotiv is the ambitious "Securing the Future of German Manufacturing Industry"[1]) has created not only a German-wide but an international landmark in terms of setting the vision, technological opportunities, and scientific challenges related to the entrance of the new generation of

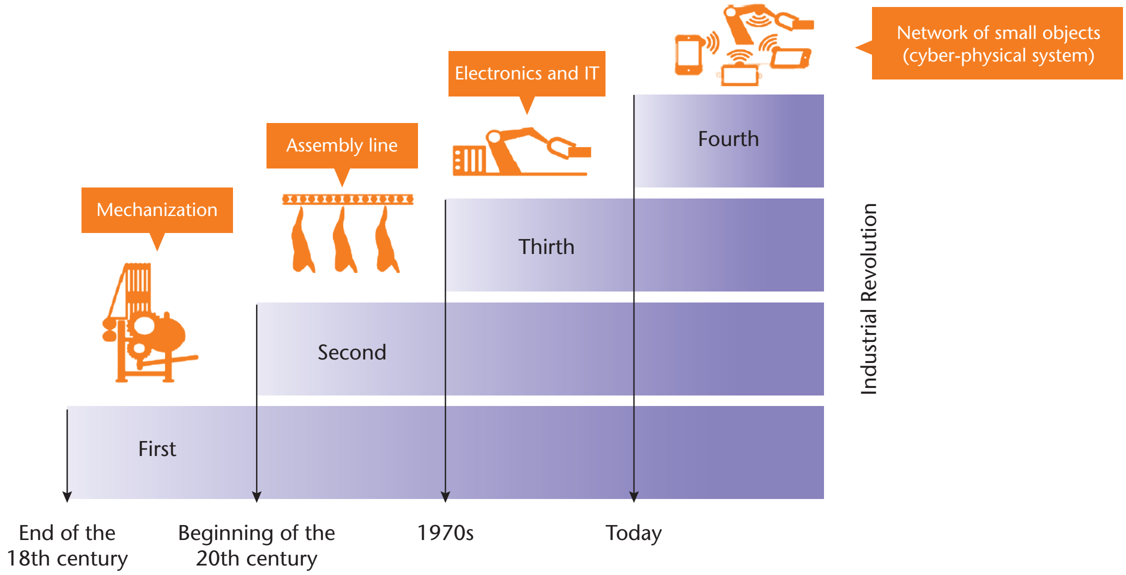


Figure 1. The fourth industrial revolution. Industrie 4.0 anticipates that cyber-physical systems (CPS) will bring about another industrial revolution.[1] (Illustration courtesy of DFKI.)

ICT technologies, including the Internet of Things and Services and CPS,[6,7] in industrial production systems.

The basic idea is that we are facing a fourth industrial revolution (see Figure 1), with disruptive applications of new generations of ICT in manufacturing. Interestingly, the CPS concept was coined by an author in the US in 2008.[8] This concept has subsequently been readily adopted in Europe by Germany in the Industrie 4.0 initiative and later by the EU in its H2020 research framework program (see http://tinyurl.com/okpfpp4). CPS refer to the convergence of the physical and digital worlds. When applied to production, CPS are specialized in cyber-physical production systems (CPPS).

Although there is some criticism regarding certain vagueness in the term Industrie 4.0 and sometimes excessive marketing,[9] it is now widely accepted that the vision and the related technologies of Industrie 4.0 have already had a real impact in industrial manufacturing systems. Reputed independent studies (including a report by Roland Berger Strategy Consultants[10]) show that the potential of Industrie 4.0 has already been realized and that its international scope is clear, especially for Europe. The Roland Berger Strategy Consultants study shows specific examples of European companies that are pioneering this trend, including Trumpf (smart social machines), Siemens (customized knee implants), and Bosch in Germany as well as Rolls-Royce (3D printing of jet engine components) in the UK, and Dassault (cloud-based collaborative 3D CAD) in France.

Figure 2 shows some of the key high-level concepts of Industrie 4.0 and Industrial Internet. The relationship between the two visions is evident, as is the relevance of visual computing.

In both the US and European visions, a strong industrial commitment with long-term associations is backed by research institutions: the Industrial Internet Consortium was created in 2014 and the Industrie 4.0 Platform in 2013.

Figure 3 illustrates some of the connectivity and interaction possibilities that Industrie 4.0 can provide. The coexistence and mutual interaction of the physical and virtual worlds, with the use of emerging ICT, opens possibilities such as

- enhanced human-machine cooperation (including human interaction with robots and intelligent machines),
- connected machine networks that follow paradigms of Internet connectivity and social networks (leading machine tool producer Trumpf[11] is an interesting example),
- improved human-in-the-loop interaction between the cyber and physical worlds,;
- networked and decentralized value chain transnational scenarios, and
- emergence of product-service networks based

Industrial Internet	Industrie 4.0
Intelligent machines Advanced analytics People at work Instrumented machines Industrial data systems Big data analytics Remote and centralized data visualization Physical-human networks	Cyber-physical systems - Physical <–> virtual worlds - Smart machines - Smart data storage systems - Smart Factories Internet of Things Internet of Services Human-environment interaction

Figure 2. Key concepts of the Industrie 4.0 and Industrial Internet initiatives. Visual computing is relevant to both visions because it offers important implementation tools, such as visualization, visual analytics, and human-machine interaction (HMI) technologies.

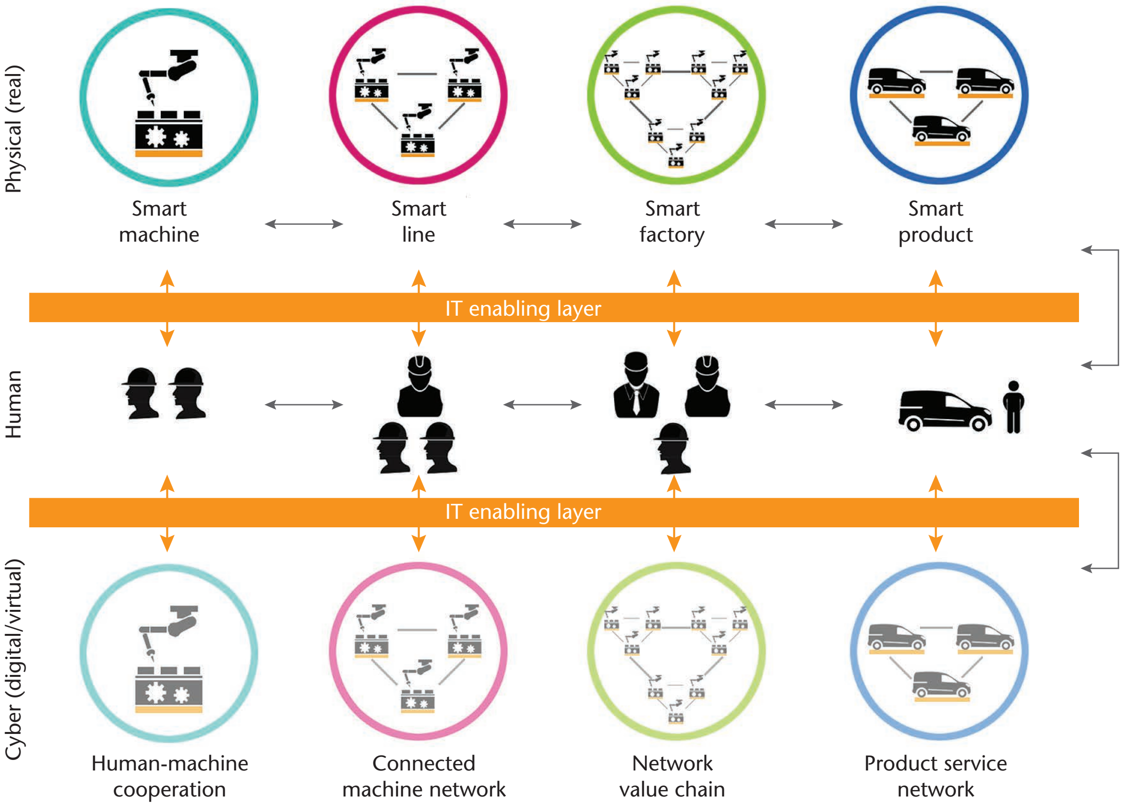


Figure 3. Interaction possibilities in a smart machine-line-factory-product scenario. Visual computing can enhance human-machine interaction as part of the IT enabling layer in different levels of smart production.

in intelligent, smart products, and associated services.

Diverse technologies such as big data, advanced HMI, 3D models and simulations, cloud computing, CPS, Internet of Things and Services, machine to machine, and smartization[12] can be applied in Industrie 4.0 solutions. Isolated, they seem to have no evident relation, but when used together in an industrial application context, their added value brings new possibilities. That is, each technology implemented separately would have a more limited impact.We argue that visual computing technologies are an important enabling technology that could act as a glue factor, an unifying element in many applications related to Industrie 4.0 and Industrial Internet. Although in several Industrie 4.0 scenarios there is no specific role for visual computing (for instance in pure IoT connectivity applications between machines and parts), in many relevant cases its role as a facilitator and integrator of other technologies sensibly enhances the final application. As a relevant example, visual analytics solutions can link industrial big data processing and mining, with semantic technologies, and product life-cycle management technologies.

Visual Computing in the Next Industrial Revolution

Historically, industry and manufacturing have been successful application areas for computer graphics. For example, the whole field of 3D CAD/CAM/CAE is a direct consequence of the key enabling capability of computer graphics in the right industrial context. Since the late 1960s, 3D CAD research has provided a competitive edge for many industrial sectors, such as automotive, aeronautic, and machine-tool. Computer vision has also been important in the industrial sector, especially when applied to the quality control and inspection (machine vision) of manufactured products and, more recently, to robotic control. Almost every manufacturing industry has such integrated systems. These examples show the strong position of visual computing technologies in modern digital manufacturing. We consider that in new generation of solutions for the next industrial revolution, emerging visual computing technologies will also play a key role.Looking to the future, a somewhat disperse collection of technologies is mentioned recursively as necessary for achieving Industrie 4.0, Industrial Internet, and other similar initiatives. Certainly, the Internet of Things and Services is a core technology that is being revolutionized by the emergence of intelligence (intelligent devices, networks, and decision technologies)[13] and complemented by cloud-based systems, cost-effective Internet solutions, secure and robust networks, mobile Internet possibilities, and so forth. But it is also true that a few key additional technologies are necessary for complete solutions, such as cybersecurity and semantic technologies.[14]

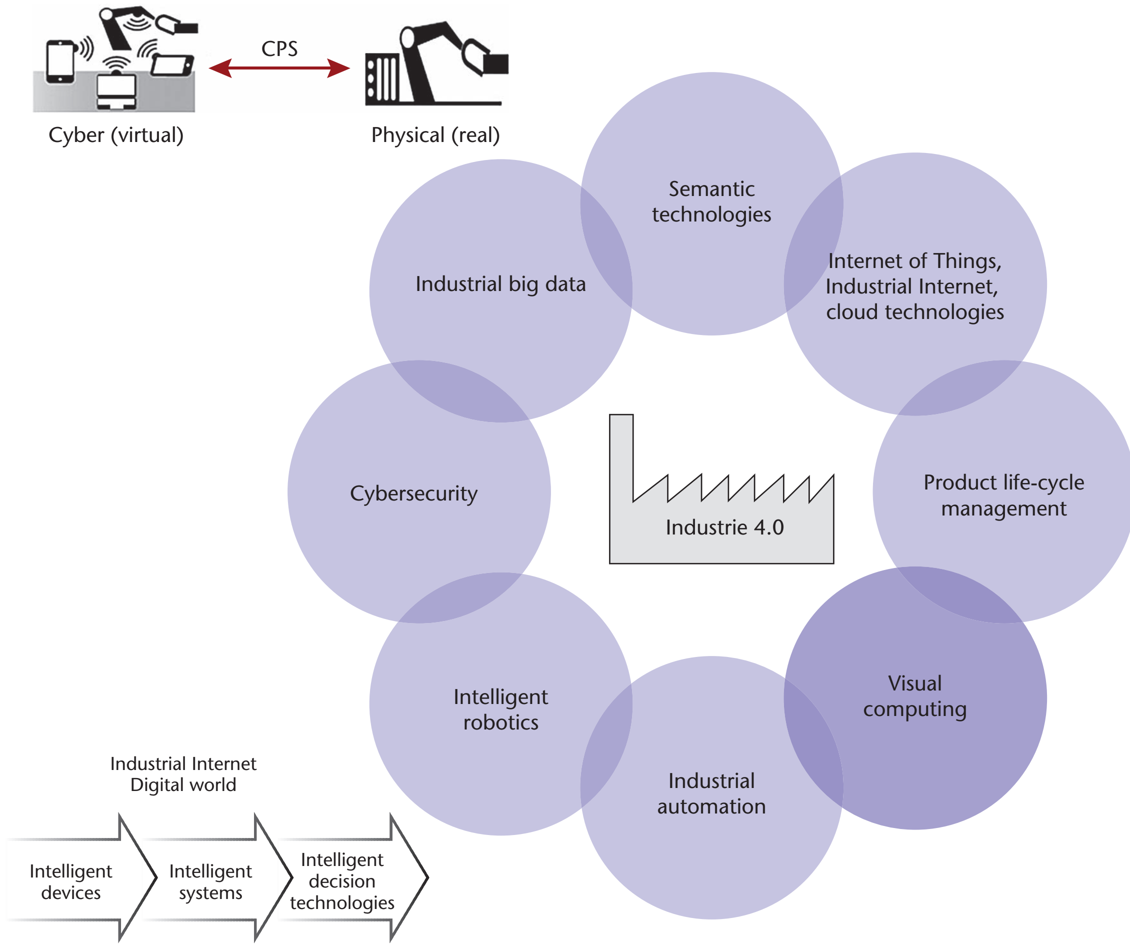


Figure 4. Visual computing as part of the technologies in Industrie 4.0. Visual computing technologies could act as a cohesion element in many applications related to Industrie 4.0 and the Industrial Internet.

Figure 4 provides an overview of this vision, pointing out the relevance of visual computing technologies (such as computer graphics, image processing, 3D, image representation, visualization, and user interfaces). A comprehensive review of relevant technologies for Industrie 4.0 from the point of view of a standardization body is available in chapter 4 of the " The German Standardization Roadmap Industrie 4.0."[15]

In many cases, we believe that the use of visual computing technologies will enhance and enable more complete and integrated solutions (see Figure 4), acting as a glue factor. This is not always the case—for instance, solutions purely based on industrial automation and IoT that don't require visual computing—but when we see the overall picture of the possibilities of this industrial revolution, visual computing indeed plays an important role and will be present in many solutions.

To achieve CPS for industry, the virtual simulation of products and processes, before and during operation, is a key aspect for achieving critical goals for product configuration and production flexibility. The modeling and simulation of processes covering the full product life-cycle (from design to disposal) is a relevant aspect, especially with the emergence of the *cyber-physical equivalence* (CPE) *concept*,[2] which refers to the fact that the virtual and physical dimensions coexist and are synchronized in time. Given this equivalence, closely related to concept of digital twins, virtual simulation can be unobtrusively overlapped with both the physical objects feeding real data in real time and the simulation model. CPE is relevant in our approach because the set of tools that will allow the inter-equivalence between real objects and their digital twins requires advanced computer graphics techniques for implementation in real-world scenarios. This addresses both the product and process levels for parts, machines and factories. Virtual simulations should be ready to cope with self-organizing production and control strategies.[16] This is a clear linking example of product life-cycle management, industrial automation and semantic technologies,[17] in which visual computing plays a central role.

A new generation of HMI applied to industry is needed to optimize the configuration of manufacturing jobs, including the operation of machines and production lines as well as aspects related to extended training and qualification. These are intelligent and multimodal assistance systems that put the person in the center of production. For instance, there are HMI related research projects financed by the German government in the program, "Virtual Techniques for the Factory of the Future: A Contribution to Industry 4.0."[18] Many of those projects address enhanced HMI development with a special focus on using personal, mobile devices with scattered and heterogeneous CPS. The traditional and de facto standards for machine operation can move toward radically new forms of interaction, including gestures, mimics, and haptics that use new forms of interaction primitives analogous to the current normalized functions and symbols for machine operation. New HMI technologies, such as multitouch and contextual menus categorized by user roles, are now even part of some product catalogs from machine-tool providers HMI developments must be aligned with CPS data gathering and be essentially oriented toward the user perspective. Such systems will incorporate the user in the factory as a knowledge consumer and producer to improve manufacturing processes.

A last example is related to industrial big data and the need for the intelligent decision making emphasized in the Industrial Internet initiative. In this context, visual analytics could help link otherwise separated technologies such as industrial big data, IoT and cloud services, intelligent devices, and semantic technologies. The manufacturing industry is one of the most demanding and challenging scenarios for visual analytics, and earlier research pointed to the many billions and even trillions of individual products that are produced per year.[19] Also, modern machines and production lines can generate massive amounts of information. A single complex machine, for example, can have a several thousand sensors that, in some cases, should be read in millisecond pulses, providing billions of readings per year. This requires not only new ways of handling the sheer volume of information, but also new forms of organizing the information so that it can be understood by humans and will allow them to make decisions. Visual analytics can help provide insights and reveal hidden patterns that are not obvious with purely automatic data mining.

Some other examples help reinforce our claim as well:

- Reference research projects funded by the initiative Industrie 4.0 in Germany, such as ARVIDA,[20] SOPHIE, ProSense, and SmarPro (see www.bmbf.de/pub/broschuere_Industrie-4.0-gesamt.pdf);
- the IntoSite project by Ford and Siemens (see http://tinyurl.com/n5ls5kg) in which geographic information systems and VR environments allow navigating global manufacturing sites and share best practice information;
- the SmartFactory Lab hosted by the German Research Center for Artificial Intelligence (DFKI) in Germany that demonstrates visual computing applications through the use of mobile devices and advanced visualization techniques (such as augmented reality, AR) for accessing and analyzing the information generated in an integrated intelligent factory; and
- the Spanish applied research project Thinking Factory led by the crankshaft manufacturing company Etxe-Tar, where visual computing techniques are applied for visualizing and analyzing big data gathered by CPS installed in several manufacturing cells to generate services such as preventive or predictive maintenance.

Figure 5 provides an analysis of the most relevant visual computing technologies, showing their significance for future Industrie 4.0 and Industrial Internet applications. This figure is a useful guide for identifying critical intersections between the priorities of the next industrial revolution based on ICT and the visual computing technologies that can act as enablers. The criteria in the left side of the figure will be explained in more detail in the next section, where we will introduce concrete examples that develop the concepts of this matrix. This matrix is by no means exhaustive, and other intersections are also possible depending on the application scenario.

In addition to showing the relevance of visual computing in this context, Figure 5 could also help align research priorities for the specific technologies with regard to the different needs of the new generation of industrial systems based on Industrie 4.0.

Research Challenges and Applications

This section focuses on specific research challenges and potential applications of visual computing for the next industrial revolution proposed by Industrie 4.0 and Industrial Internet. We order these proposals according to high-level criteria that are at the core of these initiatives[1,4] and that are depicted on the left side of Figure 5. Our purpose is to suggest interesting lines of research in each priority and at the same time show, from a global perspective, the relevant role of visual computing.

In this context, as we discussed earlier, Uwe von Lukas and André Stork argue that visual computing

	Visual analytics	Human-machine interfaces	Virtual engineering	VR and virtual environments	Augmented reality	3D Reconstruction	Cognitive vision	3D geometric modeling	Simulation/visualization	IoT in 3D/Web3D	GIS/visualization	Multimedia
Industrie 4.0: Integration dimension												
Vertical integration	■	■	■	■	■	■		■				
End-to-end digital engineering integration			■	■		■		■	■	■	■	
Horizontal integration				■	■			■		■		■
Industrie 4.0: Product and production												
Product self-awareness						■	■			■	■	■
Personalization and flexibility		■			■	■	■	■		■		
Optimized decision making	■	■	■	■					■			
New services and business models	■	■								■	■	■
Resource and energy efficiency				■	■				■		■	
Industrie 4.0: Human factors												
Work organization and design		■		■			■		■			■
Creativity of skilled workers	■	■	■						■	■		■
Training and capture of knowledge		■		■	■		■					■
Safety and security	■	■					■		■		■	
Sociotechnical interaction		■		■		■	■					■
Industrial Internet: Priorities												
Intelligent machines		■		■			■	■	■			■
Advanced analytics	■	■	■						■	■		■
People at work		■		■	■		■					■

Figure 5. Visual computing technologies relevant for Industrie 4.0. Other technologies and intersections are also possible depending on the application scenario.

can help in a bidirectional way to achieve CPE[2] in Industrie 4.0: "cyberizing the physical" (including different sensors/actuators with physically based simulation) and "physicalizing the cyber" (realistic, real-time visualization and interaction with digital models and the 3D printing area). They also provide a short summary of visual computing themes relevant to Industrie 4.0, related to geometric data models adapted to CPS, real-time simulation approaches, or image processing needs to reconstruct and cyberize the physical world. Using a similar approach, our work gives an enhanced and more comprehensive and global overview, with concrete examples, and adds an explicit link to the strategic priorities of both the Industrie 4.0 and the Industrial Internet initiatives.

Our proposed matrix structure in Figure 5 is based on three main criteria:

- integration dimensions,
- product and production priorities, and
- human factors.

Tables 1 through 3 present these challenges and applications. Computer graphics and visual computing researchers should be able to define and identify, from the context and the proposed subject, specific research contributions in each line. The tables focus more on providing a path (a roadmap of the main challenges) than on detailing each challenge. To illustrate this approach, we present one scenario for each table category.

The first criterion in our proposed matrix is integration dimensions. According to ACATECH,[1] there are three dimensions in the integration of manufacturing systems:

- vertical integration and networked manufacturing systems,
- end-to-end digital integration of engineering across the entire value chain, and
- horizontal integration through value networks.

Vertical integration allows CPS to be used to create flexible and reconfigurable manufacturing systems in factories. It refers to the integration of various IT systems at different hierarchical levels during a manufacturing process. This is where CPS play an important role as in the sensor/actuator duality. Visualizing the complex interaction between these levels might help users improve factory planning.

Table 1. Industrie 4.0 future factory visual computing challenges in three integration dimensions.

Industrie 4.0 integration dimension	Visual computing enabling technologies and challenges
Vertical integration (networked manufactured systems and autonomous cyber-physical production systems)	*Virtual environments*. Visually empowered 3D simulation scenarios for new ways of planning production, especially suitable for dynamic and fast changes. Scenarios for testing different configurations. *Real-time representation of production*. Visualizing flows of information, material, and knowledge in the factory, not only physical representation. *3D scanning and 3D reconstruction of factories*. Adapting old factories to new paradigms. *End user interfaces*. Editing configurations in demanding work conditions, such as production lines.
End-to-end digital engineering integration (holistic life-cycle management)	*Natural flow of a persistent and interactive digital model*. Product life-cycle management involving large industrial 3D CAD/CAM models with full access to semantic/dynamic integration data in Web3D. *3D real-time simulations for CPE production*. *New paradigms of 3D geometric representation*. New processes (such as laser-based manufacturing, fast-speed material removal, and micro- and nano-manufacturing) and new materials (such as biomaterials and metallic powders for 3D metal printing). *Computer vision "closing the loop" in 3D production planning*. Real-time coupling of production process and 3D models. Geometry adaptation to physical conditions.
Horizontal integration through value networks (value chain integration)	*Augmented reality (AR) for service-based actions with providers and clients*. Ergonomic aspects of the solutions going from the lab to real factories and the integration with the information systems. Intelligent media streaming/search to improve service (as in teleoperation). *3D model automatic simplification*. Preserving critical features for service tasks while allowing interaction/visualization in mobile low-power client devices.

End-to-end digital integration refers to a holistic digital engineering view, and the goal is to close the gap between product design and manufacturing and the customer (product life-cycle management). Visual computing can have real influence in this area because computer-aided technology systems are highly visual.

Finally, *horizontal integration* refers to the use of these technologies to exchange and manage information across different agents around a manufacturing process such as a resources management system, logistics, marketing, and intercompany value chain. For example, with the latest advances in devices and processing, augmented-reality-based maintenance can be an excellent case for visual computing's contribution to horizontal integration.

Table 1 shows how visual computing enabling technologies are related to the three integration dimensions. As the table shows, vertical integration in a smart factory requires a high level of communication and interaction between different production layers,. Visual computing technologies such as real-time 3D representations of data flows during product manufacturing are important enablers in this dimension.

The end-to-end integration dimension can benefit from visual computing techniques such as 3D visualization techniques for realistic product representation and simulation. Also computer vision related techniques for product quality management, both offline and online, are relevant. Online real-time computer vision techniques allow us to close the loop from product design and product manufacturing, for example, by providing immediate feedback from the real product to be compared with the digital 3D model. In an Industrie 4.0 scenario, this can be a dynamic feedback as the part is being manufactured, not a comparison between the final part and the static 3D model. Finally, horizontal integration is also enhanced by visual computing through the using of, for example, AR techniques for added-value services, such as functional or installation augmented manuals (AR manuals). Also, techniques related with 3D compression, model simplification, or model adaptation by using semantic information can be fundamental when large amounts of 3D data need to be interchanged or transferred to different entities through value networks. This problem existed also before, but it is more relevant with Industrie 4.0.

To illustrate some specific challenges that stem from Table 1, let's look at the new paradigms of 3D geometric representation for processes in more detail. For computer graphics researchers, it is a challenge to devise ways to represent 3D geometry for CAD/CAM because, as radically new fabrication processes emerge, they require new 3D representations and algorithms (for instance, slicing). For example, computational aspects of the new type of fabrication 3D printing are posing research challenges such as appropriate orthogonal slicing.[21,22] Other challenges here include devising volumetric

Table 2. Industrie 4.0 future factory visual computing challenges in product and production.

Industrie 4.0 product and production	Visual computing enabling technologies and challenges
Product self-awareness (history, status, location, delivery strategy, and service)	*Integration of GIS (outdoor) with in-factory (indoor) localization-visualization systems*. Individualized product tracking and as underlying connection layer between factories and products when delivered. *Cyber-physical 3D equivalence*. At all times linking product digital model and situational status.
Personalization and flexibility (flexible adaptation to individual customer requirements)	*3D interactive tools*. Empowering end users in the final product configuration. *Automatic generation of options catalogs*. Accounting for production parameters and user preferences. *3D shape automatic adaptation*. Fitting production and manufacturing restrictions. *Linking of 3D changes with resource impacts*. Accounting for time and cost.
Optimized decision making (with access to real-time production and design data)	*Visual analytics of production big data*. Trillions (or more) samples per year (such as GE Industrial Big Data[19]). *Real-time mixing of production big data with 3D digital engineering design data*. *User interface dynamic adaptation of information to user profile, devices, and context*. Visual analytics system for the engineer and the worker.
Emergence of new services and business models	*Digital coexistence or alter-ego of the physical product*. Enabled by Web3D, localization and mobile interaction technologies, allowing new services (such as social networks of users for the same product line).
Resource/energy efficiency and sustainable production	*Dynamic resource visualization at the factory level*. Including sustainability footprint (such as CO_2 consumption), energy distribution in a plant, and material waste. Can be mixed with VR and in some cases AR.

representations to cope with multiple materials and the sheer number of voxels.

The second criterion in the matrix, described in Table 2, is related to product and production priorities in Industrie 4.0. As a basis, we have taken the priorities explained in earlier work (see pp. 15–18, 20–25[1]) and have conceptualized, reorganized, and summarized so that the applicability of visual computing technologies is more evident for a meta-category of product and production, leaving all priorities related to human factors in a separate category. This classification also helps to more clearly bridge with the Industrial Internet priorities.

Product self-awareness is a requirement of smart products. In this context, the use of technologies such as 3D CPE to make the physical and virtual representations of parts, machines, and lines fully synchronized are essential. Optimized decision-making is one of the most critical requirements where visual analytics applied to industrial big data can give decision makers new insights. The feedback given by production data to 3D digital engineering in real time can be a key factor to model the deviation between the theoretical model and actual product. Specially adapted user interfaces are also necessary and should be adapted to the user profile and context. Web3D can provide new possibilities for the emergence of new services and business models, which is an important motivation in Industrie 4.0, technologies such as the "digital twin" or "digital alter ego" of a product. Resource and energy efficiency is another field of interest where virtual environments, GIS, simulation, and visualization open new ways to improve these aspects in Industrie 4.0. As an example, the interactive study of different logistic paths to transport parts from one factory to another can lead to energy efficiency measures.

Let's analyze in more detail one of the challenges in Table 2: visual analytics of production big data. As explained in a General Electric industry report,[19] in the manufacturing industry of personal care products, a typical real-life scenario can produce 152,000 data samples per second (in millisecond cycles), 13 billion samples a day, and 4 trillion samples per year. Visually inspecting clusters of sample data for a given time period might reveal a specific production bias due to, for instance, machine deterioration. In this context, visual analytics offers new ways to handle the complexity of this overwhelming amount of data, but such challenges can only start to be addressed today because of the advances in big data and visualization.

The third criterion, described in Table 3, is related to the human factors dimension. Industrie 4.0, Industrial Internet, and the European Factories of the Future Research Association (EFFRA) Roadmap for the Factories of the Future (http://tinyurl.com/kfxkcjx) all recognize the strategic importance of skilled workers and engineers for a competitive smart factory vision. Novel multimodal HMI and new interfaces can change the current operation of machines and factories. New

Table 3. Industrie 4.0 future factory visual computing challenges, human factors.

Industrie 4.0 relation with human factors	Visual computing enabling technologies and challenges
Work organization and design (productivity enhancement though improved human intervention)	*New HMI modalities*. Allowing new modes of interaction adapted to workers' job restrictions (such as voice-based interaction and gesture recognition) *Post-WIMP interfaces*. Adapting to the future trend of mobile devices in the factory. *Advanced manufacturing and production-planning visualization*. Linking SCADA systems with VR paradigms for interaction in the planning and understanding of the production plan. *Interfaces with manufacturing execution systems*. Allowing different configuration capabilities.
Foster creativity in skilled workers	*End-user tools for visualization of flexible production plans*. Including the location of different machines and persons (with complementary skills) in alternative production scenarios. Tools for discussions between engineers and workers.
Training and continuing professional development (capture and systematic reuse of the knowledge of the worker)	*Multimedia capture and intelligent retrieval of worker knowledge*. Capturing and transferring knowledge between the workers. *3D authoring tools and end-user UI*. Operational training of complex machines and in some cases in virtual and augmented reality setups.
Safety and security	*Cognitive computer vision systems*. Detecting and contextualizing events occurring in the factory to improve safety and security. Focusing on hazardous area exposition and collision detection with massive objects. *Visual simulation for emergency response in the factories*.
Sociotechnical interaction (co-working with configurable robots)	*Visual programming of robot interactions*. Imitating human motion based on computer vision for anthropomorphic robots. Easing the use and control of the robot by the worker, not necessarily the engineer. *Virtual environments simulations*. For human and robot coexistence in production and for different configurations and parameters.

multimedia and AR techniques can also foster the creativity of skilled workers by means of virtual simulation of production as well as and training and knowledge capture.[14] The socio-technical interaction with robots and intelligent machines is another promising area enhanced by visual computing technologies such as 3D reconstruction, virtual environments, and visual programming of robots.

As an example from Table 3, let's analyze the new HMI modalities challenge from an Industrie 4.0 perspective. A 2013 Fraunhofer Verlag technical report offers a good study on this subject and explains the challenges in detail.[23] A few of the 26 identified tools and challenges described in that work are the separation of display and interaction logic, integration of multimedia, real-time data from different perspectives, support for different HMI variants, self-learning context recognition, dynamic user profiles, interfaces to MES for a preview of simulation results, HMI design and communication interfaces for mobile devices, support for multitouch and gestures, and social aspects (chat/wiki/blog).

Example Research Projects

Here we offer three select examples of research projects directly related to visual computing applications for Industrie 4.0. Although just a sampling of potential applications, these projects cover a broad spectrum of the criteria presented in this article.

MACHS

The main goal of the R&D project MACHS is the development of a game-like 3D environment to accelerate and improve the training process of specialized machine-tool maintenance staff, prior to operating the actual machine. This project has been championedby the Danobat industrial group (part of Mondragon Corporation, one of Europe's largest industrial groups). Target system users are professional workers who have to apply their knowledge to specialized machines, that in some cases have not even been produced yet. Therefore, it is important to generate high-quality, interactive 3D environments, with a pedagogical focus, to enhance user immersion and experience. To enhance the learning experience, it is even more important to provide appropriate authoring tools and graphical interfaces so non-ICT specialists can follow the maintenance tasks during the system execution.[24]

Serious games environments can support different configuration scenarios that might arise as a result of machine adaptation to flexible production, as opposed the situation with static manuals (in the form of written manuals or videos showing specific sequences) where everything is defined in advance. In the future, this kind of environment

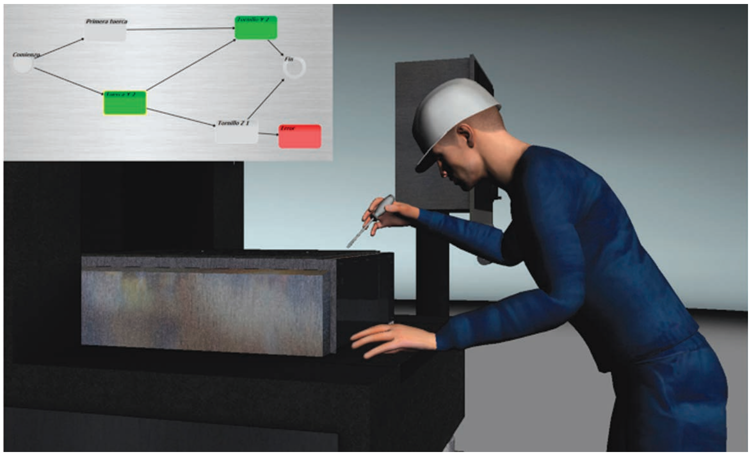


Figure 6. Immersive 3D and authoring tools for training of workers. MACHS is a game-like, 3D environment designed to accelerate and improve the training process of specialized machine-tool maintenance staff, prior to operating the actual machine.

should be automatically generated even in changing conditions (although this is still not possible in current versions of the project) and will require a preliminary definition that can evolve according to programmed rules in the game.

The preliminary definition of the worker and machine interaction in MACHS is a basis for the planning of a new generation of CPS for which, in many cases, the proper interaction between workers and machines and/or robots must be carefully monitored. By providing different training experiences in flexible configuration scenarios (such as first-person point of view versus external observer perspectives) and allowing multiple trial-and-error activities with appropriate feedback, MACHS provides a natural way to expose workers to the unknown environments of these new machines scenarios.

The MACHS R&D project is an example of how visual computing technologies can address some human factors requirements in Industrie 4.0,[1] as described in Table 3, related to training and continuing professional development so as to support the future demands of more production flexibility.

User interaction with the MACHS module // is intuitive and visual, allowing users to include 3D virtual models of specific machines and define actions directly by interacting with the machine's 3D model. The module also provides custom functions to engage the target user such as the inclusion of a 3D virtual tutor and gaming and motivational features. XML-compliant forms are automatically generated by the authoring module, which is based on an intuitive state diagram graph editor linking machine parts and worker actions (see Figure 6). The forms include virtual machine specifications (describing the machine's main functional parts and the degrees of freedom and constraints of their relative movements) and all the information that is required to build the actions that compose a training course. (The concrete specifications of these XML-compliant forms is available elsewhere.[24]) A sequence of actions is then defined where the user can simulate the machine's operation in different conditions.

The animation engine can automatically generate a 3D interactive environment from the information stored. It interactively reproduces the graph that has been created with the authoring module, reacting to the user actions in the way the course author has specified and following the rules that allow possible different configurations.

The project has been evaluated by machine-tool companies from the Danobat Group and is being tested as a prototype with their new machines for two main purposes: training and marketing.

COGNITO

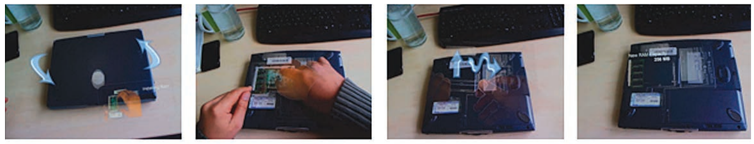
The main objective of the COGNITO (Cognitive Workflow Capturing and Rendering with On-Body Sensor Networks) project is to develop technologies that allow the capturing of manipulative workflows in industrial production scenarios in such a manner that they can be then used as training materials for adaptive AR training setups. This project focuses on the capture and systematic reuse of worker knowledge (see the Industrie 4.0 human factors in Table 3). It is also related to the vertical, horizontal, and end-to-end integration dimensions listed in Table 1—specifically, the use of AR techniques for implementing advanced HMI as applied to training and maintenance. COGNITO is an EU-funded collaborative research project connected with Industrie 4.0, and the SmartFactory KL is the leading partner for the Industrie 4.0 initiative [25]

Although capturing systems already exist on the market, they focus primarily on capturing raw motion data, matched to a coarse model of the human body. Moreover, the recorded data is organized as a single kinematic sequence, with little or no reference to the underlying task activity or workflow patterns exhibited by the human subject. The result is data that is difficult to use and that requires extensive editing and user manipulation, especially when cognitive understanding of human action is a key concern, such as in virtual manuals or training simulators in industrial scenarios.

COGNITO technology addresses these issues by advancing both the scope and the capability of human activity capturing and rendering. Specifically, the goal is to develop novel techniques that let users analyze, learn, record, and subsequently render cognitive workflow patterns.[26,27] By mapping and closely coupling both the afferent and efferent channels of the human subject, activity data can be linked directly to workflow patterns and task completion. The project particularly focuses on tasks involving hand-based manipulation of objects and tools because of its importance in many industrial applications. (See http://cordis.europa.eu/project/rcn/93576_en.html for more details).

The key element of the technology developed for COGNITO is an on-body sensor network consisting of miniature inertial and vision sensors. These sensors allow the estimation of an osteoarticular model of the human body and recover the workflow digitally, so as to develop novel rendering mechanisms for effective and user-adaptive visualization.

The work has been evaluated within the context of designing effective user-assistance systems based around AR techniques for specialized industrial manufacturing (see Figures 7 and 8) and has been carried out in close collaboration with industrial and end-user partners with promising results.



(a)

(b)

Figure 7. COGNITO adaptive AR. (a) Visual workflow using video observation. (b) AR support using previous digitalized visual workflow.

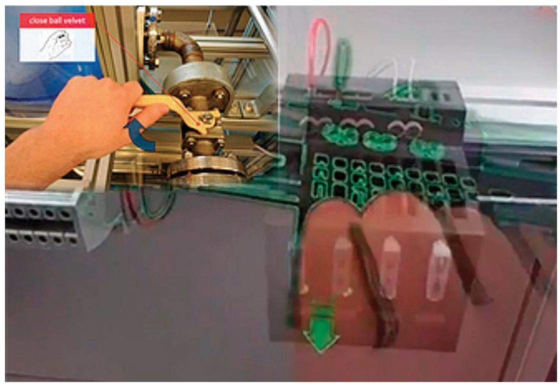


Figure 8. Visual workflow using AR manuals in COGNITO. Users see their own hands overlapped with a hand sequence previously recorded by an expert. Green indicates that movements are correct in order and tolerance.

SLOPE

The European project SLOPE (Integrated Processing and Control Systems for Sustainable Forest Production in Mountain Areas) is a rather unconventional example of how Industrie 4.0 and Industrial Internet can affect not only the factories themselves, but also important production scenarios closely related to logistics and the industrial exploitation of raw materials (in this case, wood from forests). (Consider the horizontal integration dimension introduced in Table 1.)

Mountains cover more than 35 percent of European land, which is mainly overlaid by forests. Harvester and forwarder vehicles are seldom employed in forestry operations in mountain areas, where the manual felling and extraction of timber by cable cranes is still common. The limitations imposed by mountain terrain conditions, poor road networks, and limited storage and operational space result in expensive harvesting and extracting systems that are less flexible than the cut-to-length logging systems based on wheeled machines found in the flatland forests of European Nordic countries. There is a need for more powerful and intelligent machines specialized in forest operations for steep terrain. The European project SLOPE aims to fill this gap by developing an integrated system that covers the whole cycle from forest information system to logistic transportation and allows the optimization of forest production in mountain areas. Information about material origin, quality, and availability will be integrated in a unique system, accessible online using Web3D and GIS technologies, and available in real time to a series of operators. This system is supported by information technologies such as GIS-based 3D visualization and tracking technologies. (See the project website for more details: http://cordis.europa.eu/project/rcn/110978_en.html).)

The historical series and up-to-date remote sensing data and other relevant information related to the area (such as local land-use plans, cadastral maps, and other thematic maps) will be loaded into the system. Remote sensing analysis of multispectral images will be performed to extract macro information about the forest (biomass volume, spectral vegetation indices, and growth rate). Furthermore, a combination of unmanned aerial vehicles (UAVs) or vehicle-mounted light detection and ranging (LIDAR) and terrestrial laser scanner (TLS) surveys will be planned and

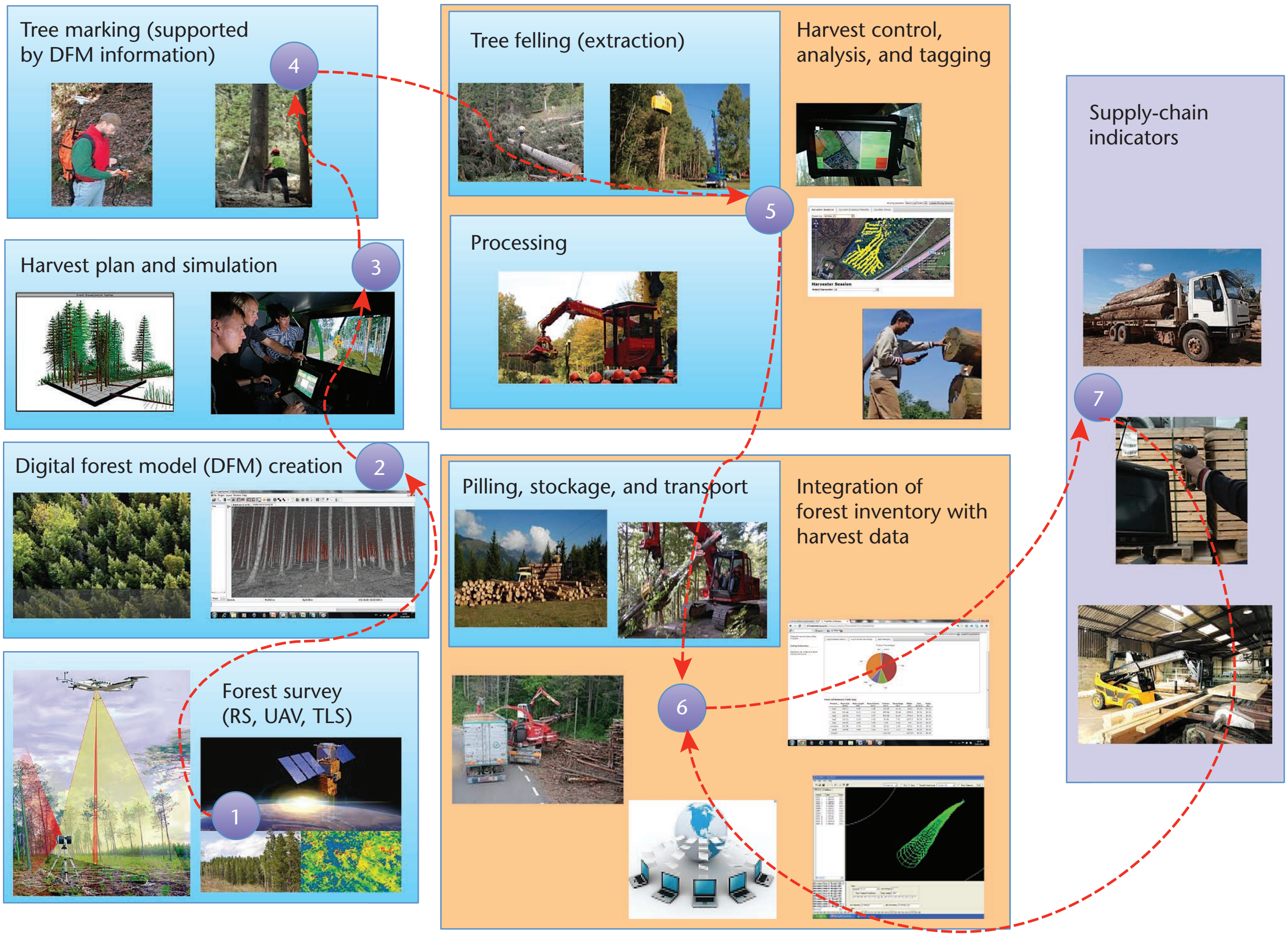


Figure 9. SLOPE project. Full cycle of logistic chains, virtual models, and flexible/adaptive production.

carried out some weeks before the scheduled harvesting operations (see point 1 in Figure 9). The processing of the acquired data generates a digital forest model (DFM), where each tree is a single object in a 3D geodatabase providing greater product knowledge (see point 2 in Figure 9).

The DFM will support forest planners in multiple criteria decision analysis (MCDA) so they can plan and simulate the harvesting operation, taking into account all possible constraints —such as infrastructural and geomorphological—and optimization procedures—such as joint forest management and coordination of harvesting of adjacent parcels owned by different landowners (see point 3 in Figure 9). The DFM will also support specific logistic decisions, such as the selection of the optimal cable crane positioning and setup. As an added application, the DFM could be used as a tool for preselling procedures, where one or more customers commit to buy the whole lot upon estimation of the volume and the timber assortments potentially available.

In this example, we could say that the smart factory location is actually the forest; the actual industrial activity happens in the forest and not in man-made physical premises. Also the products are cut trees rather than manufactured goods. However, many of the possibilities and concerns of Industrie 4.0 are still present in this case, such as logistic chains, virtual models, and flexible/adaptive production.

We have presented in this work a comprehensive overview of how visual computing can contribute as a key enabling technology to Industrie 4.0 and Industrial Internet. This new wave (or revolution) is opening new fields for productivity, business possibilities, and opportunities for securing the future of manufacturing in advanced economies. There are four compelling reasons to consider computer graphics, computer vision, and visual computing technologies as essential to these visions:

- The deep roots of 3D CAD/CAM modeling make it a key enabling technology for digital manufacturing.
- The “glue factor” capability makes it possible to integrate other key technologies.

- The virtual component in CPS of Industrie 4.0 and the visualization component in Industrial Internet address core computer graphics and visual computing concepts.
- The human factor and HMI are recognized in all these visions as one of the main enablers (people at work in Industrial Internet, people at the forefront in EFFRA/EU roadmaps, and all human factors-related priorities in Industrie 4.0).

Despite this central role, the current strategic vision documents and research literature provide a somewhat scattered view of visual computing technologies in this context. This article positions visual computing in its intrinsic crucial role for Industrie 4.0 and provides a general, broad overview and points out specific directions and scenarios for future research. The scientific community in visual computing will have new exciting fields of research linked to the challenges of the next industrial revolution.

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