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Virtual engineering based on knowledge integration

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SYNOPSIS

This paper presents major issues on actual approaches on virtual engineering, both about methods and tools but also regarding knowledge integration. The main actual strategic way of usage is based on knowledge formalization, one of the strategic issues of next generation design environments. The evolution of the market has necessitated for new products the reduction of time-to-market, essentially because the product life cycle is shorter, but also because it is very important to proceed more rapidly from an initial conception to a mass production object. As a result of newly evolved software environments, knowledge-based systems for integrated design and manufacturing is applied for complex systems obtained thanks to complex virtual extended enterprises. Due to this evolution of virtual engineering technologies and their integration within extended companies, it has become possible today to validate parts representative of customized production within a very short time. This paper provides an overview of the actual methods and tools in different components that affect speed and efficiency of product development, from the earliest stages of a product’s life cycle. An example of knowledge formalisation is also provided, with concrete aspects of expertise reuse and traceability.

Keywords: Virtual engineering, knowledge-based engineering, knowledge integration

1 INTRODUCTION

Product development, particularly product modelling [1], has become quite critical in industrial performance improvement [2]. Managing product development depends on making good trade-offs between four possible objectives in any product development cycle: (a) development speed, (b) product cost, (c) product performance, and (d) development program expense [3].
Leading companies worldwide are discovering that virtual engineering is a huge source of competitive gain, especially for new products that have not appeared previously. Recently, new elements have become accessible in the field of virtual engineering [4]. These elements enable better product definition and representation, greater efficiency of design environments, mainly a wider range of man-machine interfaces and devices, such as haptic systems and virtual reality.

This evolution in the field of virtual engineering reflects a real modification of our way of thinking product development. Thus, global coherency has emerged as a result of improved numerical integration and better software functionality for manufacturing preparation as well as for process simulation and part dimensional and geometrical control after manufacturing. This coherency, associated with improved data transfer speed and better access to information (economic and technical), leads to potential technological evolutions in the near future. These new technological evolutions have created an environment conducive to virtual engineering:

• Virtual engineering environments [5, 6] are the base for a new kind of integration of all the lifecycle models. Such approach lets engineers expect new ways of analysis and interaction with the different numerical representation and simulation models they use for the definition and the validation of the complex systems they have to industrialize always more rapidly. The challenge, which is both economic and technical, is to produce, on the one hand, special man-machine interfaces (such as haptic systems [7] and virtual reality [8]) that improve efficiency of product development environments and, on the other hand, to create software especially dedicated to virtual engineering in any phase of product and system life-cycle.

• Rapid product development applications [9], initially mainly based on reverse engineering [10, 11, 12] and rapid prototyping [13, 14, 15, 16, 17, 18, 19], continue to provide new industrial solutions for mass production. Service response time and improved manufacturing speed make it possible to expect customized production. They constitute key technologies for virtual engineering.

• Knowledge-based systems form the basis for a real integrated virtual engineering approach, using different tools and software environments at the same time. Software and new interface devices provide the means for design, simulation and product performance analysis, technological validation (manufacturability), product process engineering monitoring and management. This is what any designer and creator of new products can expect in the near future: a global and distributed environment, based on cognitive agents [20] that enables a very efficient and risk-less decision support. Most of these systems are successfully based on knowledge and success has been possible because of efficient methods to transform expertise representation, from “natural” expression to programmable languages and formalisms.

The potential evolutions outlined above illustrate that virtual engineering is both wide open and strategic. Efforts must be increased in order to find possibilities to develop synergies between industrial and academic potentials in order to make a significant contribution to the future evolution of virtual engineering environments, methods and tools.

Today's global environment [9] can enable people to go from an initial idea or object to a final object or tooling necessary for the object manufacturing. The intermediate steps go through 3D digitizing and reverse engineering, part modelling, and rapid manufacturing of parts, both directly and indirectly using rapid tooling. Knowledge and know-how regarding industrialization and the usage of new technologies should also be accessible for integration into the evaluation and the generation of the product process during the design stage.

In the course of virtual engineering, a numerical reference model coherently supports different data formats, depending on the technologies and the design process stages. Virtual
engineering requires behaviour models (for example, how to define the emergency procedures and flows for a ship or a stadium evacuation), physical models (geometrical, kinematics, dynamic, finite elements models), anthropometric representations (for ergonomic evaluation), visual and textured models (rapid 3D visualization for games, clothes representation, etc...) and many others for a realistic representation of human mannequin for in-situ use. Many efforts contribute to improve standards in order to enable interoperability between the different virtual engineering applications. Some of them relate to a more realistic modelling of material properties like heterogeneity or deformability. Note the international initiative based on the STEP (Standard for Exchange of Product model data) format [21] which is used to define heterogeneous and multi-material object data management [22, 23]. The following sections of this paper aim to provide an analysis of these influential factors in the field of virtual engineering.

2 TECHNICAL AND ECONOMIC ISSUES

A number of technical and economic criteria have had a major impact upon the ongoing evolution of virtual engineering. These criteria can be illustrated by many examples that present the diversity and complexity of the problems and the necessity for improvements. The number of examples concerning different fields of product creation is continuously growing and virtual engineering environments are also becoming strategic supports to design and industrialization validation activity. The illustrations provided in the following sections of this paper constitute some representative elements of actual projects, technologies and applications.

Many national and international initiatives are ongoing in the field of virtual engineering. For example in France, PERF-RV national project has been favoured by the Ministry of Industry in order to associate different industrial leaders and research laboratories and institutes. All the partners participate in four research and development groups that federate demonstrative scenarios to show and validate the scientific and technical progress. Figure 1 presents a picture related to some of the fundamental virtual engineering environments mainly based on specific and innovative virtual reality devices, developed and validated by the PERF-RV consortium.

Fig. 1 PERF-RV main impacts and environments [24]

Such projects have both technical and economical impacts. Researches enable the definition and the demonstration of new concepts, software and materials. These results will be integrated as the base of new product development environments. So, different companies have been created in order to industrialize the different devices and software requested by
industry for the future. PERF-RV also aimed to create a national community and to factorize the analysis of industrial needs in a very large field of applications such as automotive industry, aeronautics, energy, learning, etc... The main results of the project are prototype innovative solutions (both hardware and software), each of them demonstrating a real and effective possibility of application in a particular industrial context. Thanks to such initiatives, any company will have the opportunity to use new virtual engineering environments for a better action during the different phases of product development. For example, it is very useful to be able to verify if it is possible to assemble or disassemble a part in a complex environment without building full-scale prototypes. Figure 2 presents some specialized issues related to particular case studies on ship building (piping design during ship structure analysis [25]), on engine placement and assembly visualization during car design [26], on plane structure analysis [27].

![Fig. 3 Different industrial engineering analysis illustrations [25, 26, 27]](image)

In an integrative way of progress, it has to be considered that product and production processes have to be designed and analyzed in parallel. Manufacturability analysis is one of the most effective vectors of efficiency for product development. Plant design, associated to production lines design, let time-to-market be dramatically reduced.

**3 VIRTUAL ENGINEERING ENVIRONMENTS**

**3.1 General aspects**

Virtual engineering environments imply many constraints that are imperative conditions for their possible use in industrial environments. Of course, the main aspects of success for the application of virtual engineering environments in industry are related to simulation and behavioural models that are used for dynamic visualization and interaction, collision detection, movement tracking, 3D video projection of numerical models. When considering such environments, real time computing is one of the key issues. This is mainly critical due to the different technologies that are interfaced and synchronized, like motion capture, man-machine interfaces (3D visualization, haptic devices, sound effects, etc...). New personal computer environments enable such computation but algorithms and data formats have to be optimized.

The application fields of virtual engineering can be considered for the complete life-cycle of the product, from the earliest design stages of the products to their manufacturing, assembly, use and maintenance phases. Production engineering is widely used for the integration of
multi-view and multi-technology models. Building ships, planes or cars is favoured thanks to the use of industrial and production engineering in virtual engineering environments.

3.2 Heterogeneous data formats

In virtual engineering, mathematical models for graphical representations constitute a very critical aspect because of the necessity of reactivity and synchronization that are needed during the use of virtual engineering environments. In CAD applications, objects are mainly represented using geometric models and properties. The data formats that are used correspond to discrete and continuous geometric entities, such as points, contours, voxels, curves, surfaces, volumes (Boundary-Representation (B-Rep) and Constructive Solid Geometry (CSG)), and parametric and variational models. Information about material gradation has not yet become an integral part of Computer Aided Design (CAD) model data. Thus, down-line process planning assumes the presence of homogeneous material distribution throughout the interior of a solid. In discussing the requirements of rapid product development, however, other important aspects must also be supported, such as colour, material and physical properties (like deformability properties). Information about exact geometry, materials and tolerances need to be represented in computer-compatible format. Very often, a tessellated representation is used as a uniform and homogeneous format. Such a use contributes to accelerating the computing and simulation algorithms for many of the virtual engineering applications.

3.3 Virtual reality devices

Virtual reality [8] and haptic devices [7] constitute the most recent advances in man-machine interfaces for rapid product development and more generally for virtual engineering. Physical mock-ups are routinely used for applications such as assembly tests, accessibility and space requirements. Virtual prototyping technology allows designers to test and improve their designs earlier and with more opportunities for multi-site collaborations [28, 29]. Burdea's definition of virtual reality [30] will be used here: "Virtual Reality is a high-end user interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, taste, etc."

Visual perception is considered the most important human sense [31]. A high quality visual representation is thus essential for a good immersive impression of virtual products. In contrast to conventional screens that allow 2D viewing, virtual reality technology provides 3D stereoscopic viewing to support the depth perception of the eyes, thus providing better immersion. Using new hardware such as head-mounted-displays or multi-side projection walls (Figure 3), the view can be extended to 90-110 degrees, which is considered the necessary field-of-view for an immersive impression [32]. The third feature for a realistic visual presentation is the frequency of the image display. Due to the fact that virtual reality allows dynamic scenes (flying-through, versatile objects), the image needs to be updated regularly. The update frequencies have to exceed 15 Hz to enable objects to appear to be in continuous motion [33].
Virtual reality provides new possibilities to reduce the time needed from the first idea of a product to its mass production. It makes new simulation methods available and reduces costs without lowering product quality. Therefore, virtual reality technologies become also indispensable to the manufacturing sector.

The haptic sense is, in contrast to the visual sense, capable of sensing and interacting with the virtual environment. Haptic sensory information can be distinguished in kinetic and tactile information. Kinetic feedback is the presentation of all contact forces, including the weight of objects to the human arm. Tactile feedback provides the shape of objects to the touch receptors in the fingers. As the applications where force feedback is used are varied, no standards for haptic interfaces have yet been developed. Existing products are classified according to their different features (e.g. maximum forces or degrees of freedom (DoF)) for the use of different applications [34] (Figure 4).

In providing haptic and visual feedbacks, the geometrical data of a product received by 3D CAD systems can be displayed directly. In addition to displays of product assembly, simulations can be run which provide information about space requirements, necessary tools and accessibility [35, 36].

In the case of human immersion and interaction in the virtual scene, it is necessary to be able to capture the related location of the human body (or of part of it) into the virtual reality environment. These functionalities, named “tracking”, are needed for both a realistic modelling of human movements (in order to be able to reproduce them for the animation of a human mannequin) and the real-time interaction management of a human body with a dynamic virtual environment mainly if not using a direct man-machine interface (like 3D
mouse, force-feedback interface (Phantom from Sensable company or Virtuose 6D RV from Haption company), etc…). The Figure 5 presents two solutions for tracking, an electro-magnetic one and an optic one.

Fig. 5 Tracking systems: electro-magnetic (Optotrak, Polemus) [34] and optic (TR 16 cameras, ACTICM) [24]

The combination of these technologies is the base for the improvement of complex environment design and simulation. Such consideration has already been applied to human behaviour analysis. A demonstrator has been developed for INRS (National Institute for Research and Safety). It concerns the use of a sheet metal forming machine. The requirement is that a human can manipulate a part and interact with the machine in the same manner than in the real world. This means that the operator has the same feeling than when he manufactures a part using the real machine. The solution is illustrated below (Figure 6). The first picture represents what the operator sees, the second one the virtual reality environment [37] and the third one an improved environment with an additional system for hand tracking [38].

Fig. 6 Virtual reality demonstrator for safety analysis during a manufacturing process: first generation on the left and the middle [37], second generation on the right [38]

4 RAPID PRODUCT DEVELOPMENT, KEY TECHNOLOGIES FOR VIRTUAL ENGINEERING

Rapid product development (RPD) provides companies as well as individuals with capabilities and processes that utilize diverse technologies that enable transitions between “real physical objects” and their numerical representations used for any manipulation and simulation within the virtual engineering environments. Rapid product development is mainly based on two merged technologies: reverse engineering and layered manufacturing. These technologies are, however, still far from providing a ‘one pushbutton’ process in which an object is digitized, reconstructed, modified and manufactured. Currently, reverse engineering uses mainly laser scanners that sample an object's envelope [39]. The reconstruction methods
are dictated by this technology. Only the boundary of the object is reconstructed, and the material is not identified. In layered manufacturing, the boundary of the object in the form of a mesh (STL) is used as the input. This representation leads to conversion problems and is considered time consuming. Moreover, on layered manufacturing machines accessible on the market, mixed materials are not yet currently available [40]. Therefore, only homogeneous parts can be industrially produced.

Reverse engineering and layered manufacturing can be considered as respectively classical input and output of a virtual engineering process. In virtual engineering environments, human interacts with numerical objects that can be alternatively defined using CAD functionalities or digitized using reverse engineering devices and environments. They can also be designed in a more intuitive way by using haptic devices. In such way, it is very often of benefice to use layered manufacturing for a physical materialization of the created object for manipulation or marketing reasons.

But many other benefits have to be considered in such technologies and approaches based on reverse engineering and layered manufacturing.

4.1 Reverse Engineering

The 3D reverse engineering process has not yet reached maturity. Consequently, new methodologies are still required in order to achieve a comprehensive reverse engineering process.

The scanner technology determines the nature of the representation and the level of information available from a scanned object. It also dictates the reconstruction methods that are applied on the scanned data. The various scanning devices available on the market today [10, 11, 12] can be divided into 2D scanners and 3D scanners.

2D scanners are usually in the form of digital cameras, digital video cameras or desktop scanners. As output, they produce 2D images and movies that can be read by a computer in various formats. Their main advantage is their relatively low cost. Their disadvantage lies in the fact that information about the depth of the image is missing and therefore 3D information is difficult to extract from the images.

3D scanners, in contrast, measure and provide depth information regarding the scanned object and thus are more applicable for scanning 3D objects. 3D scanners include boundary (envelope) scanners such as CMMs and laser scanners, and volumetric scanners such as CTs (Computed Tomography) and MRIs (Magneto Resonance Imaging).

CMM (Contact Measuring Machines) devices provide positional data obtained from a probe. The probe can either be placed manually or can be controlled by a computer tracing a guide curve. A probe can measure points in places that laser scanners cannot reach due to occlusion. The main disadvantage of CMMs is their low scanning rate. Another disadvantage is the fact that a soft or inaccessible surface of an object is not suitable for contact measuring.

Laser scanners calculate reflection points from a laser beam that is projected onto the scanned object. The resulting range image is provided in the form of 3D points. Most laser scanners can scan hundreds of thousand of points within seconds at a resolution of hundreds of microns and more recently at some micron resolution. The object is usually scanned from several directions in order to provide complete information about its envelope and to avoid occlusion problems. Sometimes, however, part of the object cannot be scanned due to visibility or reflection problems.

CT and MRI are usually used for medical applications. They differ from the above scanners in the sense that they provide information regarding the interior volume of the object and not
only the object's envelope. These volumetric scanners also provide information regarding the material (density, defaults) and are applicable in quality control.

4.2 Reconstruction methods

Once data has been scanned, it must be incorporated into the CAD system through a reconstruction process. Reconstruction methods can be categorized according to scanner technology, scanned data type and geometric representation of the CAD model.

Images obtained from 2D scanners are converted to 3D geometric models based on vision techniques [41]. These techniques, however, are sensitive to the lighting conditions of the image, and prior information such as camera parameters about the projected object is sometimes needed.

The most common approach to reverse engineering today is to use scattered data obtained from laser scanners in order to reconstruct the boundary representation of the object. Reconstruction methods use polygonal boundary representation [42]. These methods are quite accurate and robust and are suitable for the fast visualization needed in virtual engineering. However, geometric representation by freeform surfaces is sometimes more suitable for engineering purposes, and thus will be elaborated.

Reconstruction of an existing object is usually based on the following stages: registration (transforming the coordinate system of the range images into one global coordinate system), segmentation (separating the points in the cloud into different regions) and 3D object reconstruction by parameterization (determining the neighbourhood between points in the range image and thus establishing the topology of the geometrical shape and its boundary) and surface fitting (minimizing the distance from the sampled points to the approximated surface). Though some of these stages may be omitted, the pattern described above appears in most methods. Figure 7 shows an original part, the digitized point cloud, half of surface model and the complete reconstructed CAD model [43].

Object reconstruction using freeform surfaces is time consuming. Time can vary from minutes to hours, and errors are still large for engineering applications (accuracy of 0.5-4% is reported in most methods [44, 45]). Furthermore, the reconstructed object is created from small surface patches whose arrangement is not intuitive for modelling. One more problem entails the sensitivity of most algorithms to non-isotropic range image data. All these problems indicate that reverse engineering algorithms are still not sufficiently mature for engineering purposes, and that new techniques and methods are needed.

Although triangulated geometry can be rigorously extracted from range images, reverse engineering techniques suitable for engineering purposes have not yet matured. In the near future, we look forward to algorithms that enable reconstruction of laser-scanned data using freeform representation. It is probable that artificial learning and heuristics will be used in these algorithms to increase accuracy and shorten reconstruction time. Until such algorithms mature, polygonal representation of scanned objects will dominate reverse engineering applications.

In the more distant future, scanners that deliver information about an object's interior and material (such as CTs and MRIs) will penetrate engineering applications, depending on technological development for engineering purposes. In such a case, not only modelling applications will be used, but analysis will be incorporated directly into the process without additional human intervention.
4.3 Layered manufacturing

Layered manufacturing is the prevailing technology in rapid prototyping applications. In layered manufacturing, a 3D CAD model has to be converted from a solid representation to 2D layered cross sections. Each layer should be well defined with closed boundaries that determine the material areas of the layer. The process usually involves face triangulation or meshing of a sculptured object and then extraction of cross sections from the meshed models (STL format).

Many layered manufacturing processes have been developed in recent years, using different materials and bonding methods [13, 14, 15, 16, 17]. Although layered manufacturing was originally used for rapid prototyping to help designers verify part form and fit (geometry), it is now progressing towards use in production of functional parts. It has also shown significant potential for the manufacture of unique and small batch production parts.

These manufacturing technologies have changed the concept of manufacturing from subtracting material to adding material. In effect, this technology can be viewed as a 3D printer in which the layers are printed sequentially. Today's layered manufacturing machines fall within the size and price range of a mid-sized computer. They can be integrated into any virtual engineering environment. The materials used in layered manufacturing machines are relatively available on the market. Maintenance is becoming simpler, but the process is still time consuming. In the near future, this 3D printing technology has the potential to become as common as 2D printers in industries, labs and private homes.

Layered manufacturing can be used for obtaining complex shapes including nested parts and complex loops that cannot be manufactured by NC machines [2].

Based upon generation of mould inserts by using layered manufacturing processes, rapid tooling methods [19] enable fast production of prototypes in final and functional materials. In order to assure profitable use of the rapid tooling process chain, it is necessary to verify whether the considered techniques are able to fulfil the needed requirements and constraints. To this purpose, decision criteria include the prototype quality, the process chain duration, the costs generated by the process chain itself and the maximum number of producible parts [46, 47, 48, 49, 50]. On the other hand, over the last several years, requirements for industrial pre-production of batch series have changed greatly. Boundary conditions are now identified in a shorter life cycle of industrial products, an increasing number of proposed variants and a quick development of innovative production technologies.

With respect to layered manufacturing and rapid tooling applications, rapid manufacturing must be one of the core interests in future development of fast production of batch series. Therefore, the basic idea of rapid manufacturing lies in the consideration that, simply by reducing time and cost in manufacturing mould inserts, only a fraction of the whole process would be affected. Taking a close look at common process chains of manufacturing parts by injection moulding or pressure die casting, it is obvious that only about one-third of the whole cycle time is spent in producing mould inserts. Aside from the production of mould inserts,
efficiency in producing parts necessitates optimization of the choice and configuration of process chains and meeting the requirement for a sensible use of CAx-Technologies. Here, too proper process organization and use of the most suitable CAx tools contribute to more efficient product development [51]. Hence, three areas, “Organizational Aspects”, “Information and Communication” and “Production Technologies,” must be managed by a correct virtual engineering strategy.

Knowledge-based engineering enables to capture and reuse expertise in different virtual engineering applications to shorten the design and industrialization phases of the product lifecycle.

5 KNOWLEDGE-BASED SYSTEMS FOR VIRTUAL ENGINEERING

Knowledge based system can be defined as a computerised system that uses knowledge about some domain to arrive at a solution to a problem which should essentially be the same as the solution concluded by a person knowledgeable, about the domain of the problem, when confronted with the same problem [52]. Such systems are software programs designed to capture and apply domain-specific knowledge and expertise in order to facilitate problems solving.

The first generation of knowledge-based system was expert systems. An Expert system is a system in which subject knowledge is held as a set of facts and rules that may be interrogated and manipulated to provide and inferred solution or explanation for a given problem [53]. This kind of systems is composed of essentially two components: a knowledge base (KB) and an inference engine. The KB is formed by a set of facts and rules that express domain specific knowledge in form of condition-action pairs referred to as a production rules. The role of the inference engine is to control the order of the rule activation. It applies specific domain knowledge to problem specific data to generate problem specific conclusions [54].

The next KBS generation was the case based systems. These systems use previous solutions to problems as a guide to solving new problems. Within these systems knowledge is stored as a set of cases, and when a solution to a new problem needs to be found, the case based system attempts to adapt the case to create a solution to the new problem [55]. Following these systems, model based systems appeared. They are based on the premise that if a good model of a system can be found, then a program reasoning from the model, could act as an expert in understanding the system [56]. In addition, it is possible such a system could be developed more quickly and provides more comprehensive coverage of problem areas [57].

Knowledge based systems are widely acknowledged to be the key for enhancing productivity in the industries, but the major bottleneck of their construction is knowledge acquisition, i.e., the process of capturing expertise before implementation in a system [58]. To face this problem, several methodologies have been suggested. The methodologies have been aimed at assisting the developers to define and model the problem in question, such as Structured Analysis and Generation of Expert Systems (STAGES) and Knowledge Acquisition Documentation System (KADS) (an acronym that has been redefined many times, e.g. Knowledge Acquisition Documentation System and Knowledge-based system Analysis and Design Support).

Among the proposed methodologies, perhaps, the most widely known one is CommonKADS methodology. It supports project management, organisational analysis, knowledge acquisition, conceptual modelling, user interaction, system integration, and design. It describes KBS development both from a project management perspective and a results perspective. The latter considers KBS development as the continuous improvement of a set of models of various
aspects of the KBS and its environment [59]. The CommonKADS methodology is large and complex, it can be difficult to learn, and the effort required for its implementation would be disproportionate for small companies and small projects [60].

Adding to the methodologies’ complexity and the knowledge acquisition issues, the proposed methodologies for KBS development have normally been applied to areas other than the engineering design area, and have not been commercially used for knowledge based engineering (KBE) development.

Knowledge-based engineering sometimes referred to as KBE deals with processing of engineering knowledge. It is a process of implementing KBS in which domain specific knowledge regarding a part or a process is stored together with other attributes.

Currently, many industries have recognised the value of the KBE technology, this recognition is illustrated by its acceptance as an important and successful tool in the aerospace and automotive sectors among the technologies supporting automated design.

5.1 Knowledge Based Engineering

Engineering knowledge tends to be very complex, diverse, and interrelated in many ways. Consequently, knowledge modelling in engineering must be based on a rich and structured representation of this knowledge, and an adequate way of user interaction for modelling and using this knowledge [61]. Due to the complexity of engineering knowledge, knowledge modelling in engineering is a complex task. Many relations and interdependencies have to be taken into account in order to come up with a model that is as precise, generic, consistent and concise as possible [62]. So, each new piece of knowledge, which should be inserted into an existing knowledge model, has to be related in many ways to the already contained knowledge. Thus, during modelling a maximum of information about the already existing model has to be available and easily accessible by the knowledge engineer.

The other main knowledge related issue in engineering is the application of knowledge-based technologies, i.e., the automatic computer based processing of knowledge in KBE systems.

The two following paragraphs define the concept of KBE, the most known existing methodologies and mostly used modelling techniques to support such technology.

KBE has been defined as being an engineering methodology in which knowledge about the product, e.g., the techniques used to design, analyse, and manufacture a product, is stored in a special product model. The product model represents the engineering intent behind the geometric design; It can store information attributes of the physical product such as geometry, material type, functional constraints, etc. as well as process information, the processes by which the product is analysed, manufactured, and tested. The KBE product model can also use information outside its product model environment such as databases and external company programs.

In reality, there is no unambiguous definition of KBE, however, all of proposed ones are similar. KBE has been defined as a computer system that stores and processes knowledge related to and based upon a constructed and computerised product model [52].

Bermell-García [63] defines it as a special type of Knowledge Based Systems with a particular focus on product engineering design activities such as analysis, manufacturing, production planning, cost estimation and even sales.

Another definition given by Chapman and Pinfold [64] describes KBE as an engineering method that represents a merging of object oriented programming (OOP), Artificial Intelligence (AI) techniques and computer-aided design technologies, giving benefit to customised or variant design automation solutions.

However, all these definitions agreed on the fact that the basic objectives that have to be supported by KBE are: solve a particular design problem by a KBE application (short-term),
and retain the domain knowledge required for solving design problems in the same domain (long-term).

Recently, companies realized that product-related activities should start to be considered on a systematic basis [65]. KBE has then gradually gained prominence as a major tool to speed up product development. The encoding of design knowledge from domain experts into computer codes, that can generate complex geometric data, has demonstrated significant savings in manpower and time resources for routine design problems [63], and has also provided a high degree of design integration and automation in well defined and complex design tasks. Instead of replacing CAD technology, KBE complements it by offering an environment to automate design activities as well as the means to build a structure in which product knowledge is encoded and stored using an advanced programming language. This language is usually based upon the object-oriented knowledge representation paradigm.

There is a number of different methodologies available for KBS systems; however, only few methods are focused on the development of Knowledge-Based Engineering systems. Among them we identified the MOKA ¹ and KOMPRESSA ² methodologies. The MOKA methodology has been proposed to address methodological issues during KBE systems development. It was part of results from the MOKA³ ESPRIT project, a project that aimed to develop a standard methodology for the development and maintenance of KBE applications. One of the project’s aims was to allow the lead-time for the development of an application to be reduced by up to 25% [66]. This methodology will be presented farther in the paper. Within another context, KOMPRESSA has been proposed within the REFIT⁴ project, at an applicative level, with the principal aim of developing a methodology that is suitable for SMEs, most importantly, this means minimising the time, effort, and expense needed for system development, without sacrificing quality and maintainability [67].

Other research works related to the use of technologies such KBE in specific domain have been done through cases studies. Among them, we can mention those of Chapman [64] that reports on the use of KBE technology in the creation of a concept development tool, called DART⁵, to organise information flow as architecture for the effective implementation of rapid design solutions in the automotive industry. There is also the works done by Santiago, within the KBEMOULD⁶ project, on the validation of a KBE tool for the automatic and distributed design of plastic injection moulds for the plastic and toy sector; And those of Bermell-García [63] reporting on the experience of the development of a KBE system for the design and manufacture of a wind tunnel testing model of an aircraft nacelle.

The overall works presented lead us to state that the common aim of all these works consists in proposing structures for knowledge capturing and modelling. The most used modelling techniques are introduced in the following section.

As mentioned above, the aim with the KBE system is to solve a problem that can be solved by a human expert in the domain. This means that the knowledge that the expert processes has to be translated so that the computer can use it. To reach this purpose, engineering knowledge has to be correctly structured in KBE application codes. In terms of developing KBE applications, this structuring process involves the configuration of the objects that model the engineering design environment and the rules that control the behaviour of the objects [62].

¹ Methodology and tools Oriented to Knowledge based engineering Applications
² Knowledge-Oriented Methodology for the Planning and Rapid Engineering of Small-Scale Applications
³ http://web1.eng.coventry.ac.uk/moka
⁴ Revitalisation of Expertise in Foundries using Information Technology, carried out at the Knowledge- Knowledge Engineering and Management (KEM) Centre at Coventry University.
⁵ Design Analysis Response Tool
This constitutes a process of abstraction that in the KBE environment can be stated as follows: "The process in which the engineering knowledge is analysed for being represented in terms of objects and Engineering Rules (ERs) in a computer understandable language" [68]. Knowledge modelling has been extensively researched and different representation schemas have been proposed such as logical formalisms, semantic networks, frame-based structures, rule-based representations and object oriented representations. Current KBE systems are based upon a combination of the production rules and the object-oriented knowledge representation. Both elements together offer an automated way to introduce design requirements, model design constraints and provide a product description.

As it has been reported by Bench-Capon [69] the combination of both paradigms results in a powerful knowledge representation strategy by combining the flexibility of rules with the capabilities for modelling real problems of object-oriented data structures. And the adoption of both knowledge representation paradigms has been widely recognised as highly effective to exploit the benefits of CAD and the feature-based geometric modelling approach [63].

5.2 USIQUICK: a KBE system development project
The works presented here are part of the output from an industrial project, called USIQUICK, financed by the French Ministry of Industry. The project was started with the aim of developing a knowledge-based engineering system to help experts to define the process planning for mechanical parts.

The project focuses on the definition of milling process plans in aircraft manufacturing with a high amount of re-engineering and this implies particular geometries and processes.

In order to optimise the information flow from design to production, a three-step method is proposed [70]:
- Transformation phase: an analysis of the part to compute a maximum of information registered in an appropriate level of feature. In this phase computer assess the manufacturability of faces.
- Preparation phase: the synthesis templates of the previous phase are presented to the user. Then with appropriate tools, the process plan skeleton can be built and constrained.
- Automation phase: the unconstrained choices are automatically optimized and a complete documentation is proposed by the system.

These phases would become the three major modules of the engineering tool based on the formalisation and the integration of expert knowledge.

The project involves eight partners:
- An aircraft manufacturer was in charge of specifying the expected results. He also proposed his expertise on complex part design and on process planning.
- A CAD/CAM development leader planned the industrialization of outputs in its software solution.
- Five laboratories had the responsibilities of ensuring the scientific coherence of the project and proposing innovative solutions to solve strategic locks.
- A French-government institute analysed the possible use in other fields and proposes extra test cases and tool databases.

The different partners started working together in a same setting domain with different cultures, contexts, goals and backgrounds. These differences led to different viewpoints, assumptions and needs. Furthermore, they used different jargons and terminologies sometimes diverging or overlapping, generating then confusions.

7 www.usiquick.com
Our role in the project is to propose solutions to allow these people from different organizations to effectively cooperate on the same objective despite the mentioned differences, and to reduce the communication gap between the domain expert and the developer. To make this cooperation possible we proposed to put at their disposal contextualised and structured information, in form of knowledge, to help them for having a shared understanding of the domain, the context and the goals.

However, to develop a KBE system we need to acquire, to represent, to reason and then to communicate the intent of the design process. The problem is first understood at a conceptual level, and then decomposed into understandable working objects, developed further through an iterative process until a satisfactory outcome is reached. Then, product and process development are defined as a logical sequence of stages or activities, which may be documented, disseminated and understood by the by all actors [65].

One of the project’s challenges is to translate knowledge that has been expressed in form of legacy specifications for the development of the system into a computerised form so that the computer can use it. The difficulty is thus to select the right methods and tools for supporting and structuring such transfer. One solution could be to structure the knowledge within a knowledge base (KB). The building of this KB implies the deployment of a capitalization process to help and guide the knowledge treatments. Capitalizing knowledge consists in processing and treating knowledge to prepare it for management activities. This capitalization will enable knowledge to be shared through a specific form making it understandable by each actor of the project.

Knowledge capitalization is the process of capturing and formalising expertise before its implementation in a system. The aim of knowledge capitalization is to develop methods and tools that make the task of capturing and validating knowledge experts as efficient and effective as possible. Experts tend to be important and busy people; hence it is vital that the methods used minimise the time each expert spends off the job taking part in knowledge acquisition sessions [52].

To reach the multi-experts collaboration, the knowledge sharing and reuse within the USIQUICK context, we propose to capitalize the knowledge in two major phases: a capture phase and a formalisation phase.

The capture phase gathers the elicitation, the analysis and the structuring stages, while the formalisation phase is the representation stage. In the following sections, only the capture phase will be detailed.

5.3 Capitalization process proposal

According to the KBE systems development principle, knowledge must be identified, acquired, analysed, structured and formalised in a way that it could be accessible and reusable by each one.

What we are proposing in this paper is not completely different or contradictory with KBE development principle. Our aim is to structure all these activities according to the knowledge aspect addressed at each stage of the capitalization process. This structuring consists in separating the activities that handle the knowledge itself from those handling its form. This distinction tends to help knowledge engineers during capitalization activities deployment.

This structuring can also been considered as working on the knowledge’s state. Indeed, working on the knowledge content consists in transforming its state from a raw state (independently of being explicit of tacit) to a structured one. And working on the form, deals with the representation of the knowledge to go from a structured state to a formalised state, and further toward an automated one.
The transition between the two phases rests on the design of a knowledge base. This base constitutes a knowledge repository that can be accessible and which will be the knowledge reference for the whole involved partners (Figure 8).

Knowledge capture is the process that tries to transform the human experts’ knowledge into a formulated knowledge that can be used directly by an expert system or by a computer system. Within the USIQUICK project, the expert gave us some pages with text and schemas.

Among the existing methodologies for KBS and KBE development, the only one that can meet our needs is MOKA methodology (Methodology and software tools Oriented to Knowledge Engineering Applications). This is because it offers the possibilities of extracting knowledge from documents within engineering domains through its ontology. MOKA provides a framework both for capturing and for representing Knowledge. This framework works at two levels: informal level and formal level. The first one is relatively simple and oriented to represent and formalize knowledge in language that can be understood by experts without being specialist in formalization languages. The advantage of this level is that it makes the validation of the acquired knowledge possible. This level makes also the communication between the expert, the knowledge engineer and the software developer easier.

The second level is more formal and aims to represent and store knowledge in an encoding forming in order to plug it into computers. MOKA proposes five generic knowledge object types and relations among them to describe the domain. These objects are also defined as well as their use constraints. These object’s types are: 1) Illustrations representing comments, past experiences, specific cases and complex explanations; 2) Constraints describing the product’s or its component’s limitations; 3) Activities to describe problems’ resolution stages; 4) Rules to describe knowledge that directs the choices in the activities; 5) Entities to represent knowledge elements that describe the product, its components, its assemblies, parts and features. An entity can be structural or functional.

Starting from this ontology, the first step was the identification of the knowledge objects. The identification step is a preliminary investigation and analysis that aims to recognise the knowledge elements or objects that must be acquired. The specifications we got consist of...
texts, tables, and images in MS Word format. The domain library, which approximates domain ontology, consists of technical sentences condensed from legacy specifications. We proposed an extended ontology, by adding two new concepts, Functions and Resources. The use of the ICARREF MOKA-extended ontology, which is based on a few concepts (Figure 9), allowed us to identify a great number of knowledge objects.

At this stage, part of the knowledge can be extracted using a method that allows obtaining structure of the concepts contained within the text given by the expert (Figure 10). Before extracting the knowledge it must be analysed. The analysis step is the most difficult step among the stages in the knowledge capture process because the belief is that a «magical one-to-one correspondence» between the expert’s verbal comment and the real items of knowledge is misleading [60]. Data and information obtained from manuals, textbooks, experts, and even users need to be converted into knowledge before they can be used. This means that it is necessary to identify the interrelated knowledge components, and after, to define the right relation for each linked components. Different relation types can be defined, for example: “has constraint” to link entities to constraints, “has function” between functions and activities, etc. Therefore, these concepts and relations are coded with ICARREF forms, then converted to UML diagrams and, finally to C++ software development (Figure 11).
Fig. 10 Knowledge analysis, extraction, structuring and diffusion

Fig. 11 Knowledge structuring step from ICARE model to C++ development
5.4 An other example of a complete knowledge-based integrated system in manufacturing field

The integration of numerical development technologies for casting industries allows equally to define casting products, casting processes and tooling, and to simulate the defined processes, allowing thus inserting an intermediary step of validation. It is then possible to perfect the operational processes before their deployments, reducing the risks, the delays and the costs linked to the perfect operational processes.

The adopted solution was to propose a commercial system as the base for 3D modelling for several reasons: its price, its friendliness, its performances, its development capacities, and the reactivity of its commercial organization. The friendliness of software mainly depends on its performances. Besides modelling capacities, the easy use of the functions allows multiplying the loops in order to test different solutions (in particular for the management of the subcontracting activities).

But the standard functionalities of this CAD tool were limited to the modelling of foundry parts and were not sufficient when considering a global numerical engineering perspective of the casting process components definition. It has been necessary to develop an environment of supplementary functionalities allowing deploying the proposed engineering methodology.

In foundry, some significant developments should allow in a medium term improving standard software performances regarding conception oriented trades [71, 72, 73]. But, based on our experience and on the company expertise, we proposed first our knowledge-based methodology for the modeling of raw foundry parts. The first step consists in obtaining a rough idea of the 3D piece. On this basis, the technician models the outlines of the raw part by realizing the necessary adaptations (draft angles, filets, etc...). A particular possibility allows optimizing the weight of material while considering the mechanical properties of the final machined part.

After designing the raw part, our methodology is adapted for the modelling of the features describing the casting manufacture process. So, in an integrated approach, the patterns, the tools, the cluster, the cores and the core boxes are automatically defined, based on the expertise integrated in the virtual engineering knowledge-based tool.

The design phase must result in casting parts and tools in accordance with the capacities of the production unit and compatible with the sand casting process. The global objective remaining the minimization of the scraps and the direct manufacture of parts in accordance with the production plan, the integration of numerical simulation tools gives assistance for the validation of the products and processes.

The complete proposed approach has been implemented and this was a success [74, 75, 76]. One of the key factors of this success was the integration of all these methodological and technological expertise of the operators, technicians and engineers.

This approach can be summarized by the Figure 12. This figure represents the key elements of the new integrated process that has been implemented in the casting company. The main benefits nowadays are mainly the reactivity and the capacity of replying to any customer demand and also to be able to link in a direct and integrated way, all the processes of the company, from the costing to the part delivery. The estimation of the impact of a given production on the company results has also been as an original approach. Economical aspects are now completely integrated and linked to the technological factors of the enterprise processes. Thus, it is possible to optimize the product cost in order for the company to be competitive in a very concurrent ness open market.
5.5 Three examples of virtual engineering applications in other fields

In the previous sections of the paper, we have described some bases for virtual engineering definition and integration. Two examples have also been presented in order to let the approach be more explicit. Our experience concerns several domains that are not limited to manufacturing processes. The proposed approach and concepts can also be applied in many fields along the definition process of the systems.

Fig. 13 Sand casting cluster finishing unit [74]

During the study concerning sand casting industry, we had to solve a bottle-neck problem along the production flow. The finishing of the casting parts was done manually in very difficult conditions for
the operators. It has been decided to model and simulate a cell environment (Figure 13). The basic idea is to let a robot take the cluster and put it under an optical-based scanning unit. Then, after identification of each of the parts of the cluster, a second robot takes the cluster and moves it in front of the cutting unit with a position calculated from the results of the scanning system. This cell has been functionally defined and modelled within a commercial environment. Then the simulation of the production batches has been possible in order to evaluate the compatibility of the cycle time with the constraints of the scanning and cutting technologies that are used.

In the previous example, there were no human in charge of critical task in the cell. It was not necessary to simulate the compromise between risk and productivity. But, very often, humans are involved in potentially dangerous missions that can be simulated before doing them, for a given environment. Such approach can also allow the designers of industrial systems and environments having some indicators for the comparison of different configurations of the system, and for the evaluation of the efficiency of some safety barriers. In a recent work, we propose an information model integrating safety expertise for the modelling and the simulation of human behaviour within an industrial system [77, 78, 79]. These concepts have been implemented in a commercial system environment. The Figure 14 presents a screen shot of the developed application.

![Fig. 14 Screen shot of the application for human risk analysis [79]](image)

This kind of approach is very useful for so many applications related to actual technical systems that it has also been applied to old technical systems and environments. The problem nowadays is to capture the maximum of information from a “physical dead” system in order to link this information to historical repository. The idea is to define a knowledge-based system for the modelling and the simulation of an old technical system or environment [80, 81]. The complete process starts from the digitizing and the CAD modelling of the key features of the systems in order to exploit this numerical information in different valorisation contexts (internet, virtual museums, virtual reality immersion, etc…). This kind of numerical integration allows surfing within all the information related to the system, its components, its environment, its users, the industrial and social contexts, etc… This is very much efficient compared to a classical approach which is more “paper-based”. The Figure 15 is related to a printing unit. The original machine is on the left on the figure, the numerical model including the role of humans is on the right. The figure 16 shows something a bit different. This is a salt washing environment. This was used to let the salt extracted from the sea to be washed using a particular liquid-based substance. On the top of the Figure 16, this is the environment as it can be seen now. On the bottom, on the left, this is the data obtained by a teodolhit laser that scanned the complete environment. On the right, this is the environment modelled with a commercial CAD system. This CAD system can be used for immersion in a virtual reality environment in order to see in detail the
kinematics principles used in this kind of machine. It has to be indicated that for such problem, it has
been necessary to use different measuring solutions and systems, like portable laser scanners for some
particular mechanical parts that were very much damaged by the salt. Then, the CAD functionalities
allowed “repairing” these parts and the numerical model is impressive for the people in charge of the
salt museum because it is possible to see the machine moving and to understand and measure its
performances. Some comparisons are possible with some historical economical data related to salt
production in the period of use of this machine.

![Image of printing machine and CAD model](image1)

**Fig. 15** Photo of the printing machine and screen shot of CAD model including human operators [81]

![Image of salt washing machine and CAD model](image2)

**Fig. 16** Photo of the salt washing machine, scanned data from the laser sensor and
screen shot of CAD system [81]
6 SUMMARY

This paper has aimed at presenting a synthesis of today's trends in virtual engineering, taking into account new technological directions as well as new solutions for product development environments. Some benefits of knowledge-based systems have been illustrated, both on methodological and practical aspects.

The effect of the digital revolution on the design and manufacturing world is producing profound changes in the traditional product realization paradigm. The creative evolution of virtual engineering will continue to generate a variety of new environments to design, simulate, validate, industrialize and manufacture products with broad capabilities for meeting customer expectations.

Design process management must be improved because experience is mainly related to an internal design process with only a few actors. The design process is becoming increasingly difficult to manage because of the number of actors and the complexity and dynamics of design organization. Electronic access is a great advantage in order to exchange and to communicate with anyone around the world. It is also a significant vector of complexity because of the organization effect. For these reasons, the scientific community has to significantly reinforce the work already initiated on product, process and organization interactions in order to focus on a real integration during virtual engineering phases.

To summarize, the benefits of virtual engineering can be fully realized only with resources organized in order to achieve high flexibility and quick reactivity to changes. Furthermore, an appropriate choice of CAX tools provides valid support in preventing compatibility problems in data communication between the different tools, mostly based on knowledge. Interoperability will be a key issue for the next generation of product development environments.

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Reverse engineering for industrial heritage: 3D digitalization

ABSTRACT

Nowadays, digital document is becoming the standard way of working: travellers have lighter bags but mainly transmission of such documents is faster, and their use is far more convenient to search into them. Consequently, digitalizing physical paper is also very common: many people own a scanner at home. But what about objects? 3D artefacts also need to be digital. CAD software is nearly always used by enterprises for designing their product. But what about old objects, old machines, 100 years older or even more? These basics of technical knowledge have also to be digitalized. 3D scanning technologies are fully emerging in Industrial Engineering. Our scientific researches are targeted on old objects issued from heritage. We propose to virtualize them. But 3D scanning technologies need to be customized as we are working with patrimony where sometimes it is impossible to lighten the object or to move it... The aim of this communication is to define a methodology using a decision tree with adapted operators for digitalizing old objects respecting patrimony conditions. In addition, we illustrate our research with two examples where it has been used digitalizing technologies.

Keywords: reverse-engineering, 3D digitalisation, heritage
1 INTRODUCTION

Nowadays, the situation of the technical and industrial heritage raises many problems: how to manage and valorize it in case of Museums and sites? How to ensure life prolongation for the technical information of the collections, archives and heritage places? This technical information, testimony of the past, are coming older very fast; like a puzzle which parts wear or disappear, the technical data dispel progressively with the time. That’s why preserving the national technical patrimony has now become a priority of governments and world organizations. Our approach proposes a new kind of finality: as saving and maintaining physical object cost a lot for museums, and sometimes dismantling is impossible as the machine falls into ruin, we propose to preserve it as a numerical object.

In the first part of this communication, we explain why preserving objects under a numerical form can be a solution for museums; we expose the global methodology developed, merging Industrial Engineering Sciences and Social Sciences. Next, a state of the art and a classification is established about the 3D digitalization tools. Finally, we illustrate our gait with examples.

2 SCIENTIFIC AND TECHNICAL HERITAGE RESCUE

2.1 Initiatives for capitalization and virtualization

The protection of scientific, technical and industrial heritage is a rather recent idea. It is in England, during the Sixties, that was born what British people call the "industrial archaeology". The first experimentation object for the capitalization and the valorization of the heritage was the Ironbridge (it was the first iron bridge, built in 1779 and classified to the world heritage of UNESCO in 1986) [1].

Initiated in 1992 by the French culture and communication Ministry, the French research and technology Ministry, and the French Education Ministry, the REMUS project was the first one that had developed interdisciplinary teams in order to find new solutions for the museology of sciences and technology. Several works and studies were finalized: the main point was to give advises when using audio-visual technologies [2]. But, in term of museology, no new didactic methods have been developed since 1992.

In 2003, at the ICHIM conference, Jean-Pierre Dalbéra from the French culture and communication Ministry stressed on the need for a capitalization and a valorization of the French heritage [3]. Since this communication, many research programs have been started in France; among them, we can mention:

- GALLICA, digitalization and diffusion on the Web of books from the French National Library "François Mitterrand" in Paris (France);
- CNUM, digitalization and diffusion on the Web of books from the French National Science and Technology Academy "Musée des Arts et Métiers" in Paris (France).

However, those projects are focused on historical documents, images, art objects or architectural monuments… The technical industrial heritage has not been targeted as a priority for conservation.

It should be noticed that a first project was initiated by the French culture ministry under the heading: "Scientific and technological innovation memories of the 20th century" [4] [5]. This project was managed by Yves Thomas, director of the research valorization service of Nantes University, and by Catherine Cuenca, national museum curator from the French National...
Science and Technology Academy "Musée des Arts et Métiers". The main characteristic of this project is that new technologies are used for valorization of the capitalized heritage; 2 DVDs were produced relating researchers histories and objects histories; in addition, a website was created allowing everybody to access to this knowledge from expert or for ludic games or even for teaching (using the module for creating presentations) [6]. But those valorization elements are only the visible part of the project; indeed, the whole study consists of a large data base of more than 3000 referenced and documented objects used for researches from Western Region of France. Recently, the program has been extended up to a national scale.

2.2 Which knowledge has to be capitalized?
In its book "the objects life ", Thierry Bonnot, anthropologist, consigns that "an object takes a meaning only in a human context" [7] . A machine or a system is significant only if it can relate a social act and if it can help to conserve all the aspects of a technical culture, i.e. the physical objects but also the vestiges it contains: gestures, know-how, social relations... The object study cannot be dissociated from its context (know-how, political context, social context, economical context...). Just like the photocopy gives back the object within its framework, the sound track on which it has been consigned critical information for understanding the object or the written report on which the auditor has reported the human context, all those elements allow re-contextualisation of the object (Rolland 2001).
Depending on the desired finalities of the valorization, it will be advisable to capitalize all the necessary knowledge for achieving this goal. Thus, dealing with old technical objects, knowledge to be capitalized can be represented by the mapping of figure 1. This pattern reminds the concept previously mentioned for the object definition and the context definition. The design flow mentions comes from the flow definition of the Functional Diagram Block of APTE method.

![Fig. 1 Mapping of the definition of a physical object](image-url)
3 HYPOTHESIS AND METHODOLOGY

3.1 What about engineering sciences? Real or digital mock-up?
For capitalizing knowledge, many methods are used but it is not the goal of this communication. However, once the external knowledge captured, remains the conservation problem of the physical object. So as to resolve this problematic, the engineering tools and more widely virtual tools and computer graphics can help.
As Olivier Lavoisy demonstrate it in its thesis [8], evolutions of the technical drawing (he prefers to use the term: graphical techniques) are becoming really powerful since several years. Then, after numerous analyses, he raised the conclusion that graphical techniques are more than one hard copy: "graphical techniques seem they are playing a role in the transmission of know-how within the workshops, within the training centers and into academies".

| …-1990 | 2D Paper |
| 1980-… | Computer Assisted Design (CAD) |
| 1990-… | Product Data Management |
| 2000-… | Digital Mock-Up |
| 2005-… | Virtual Manufacturing |
| 2008-… | Digital way |

Fig. 2 Evolution of graphical techniques [9]

Nowadays, digital mock-ups are used for replacing physical model. It is possible to carry out various functional simulations, to try various aesthetic design... Moreover, in virtual reality domain, tools have been developed so quickly that virtual simulations of dynamic situation are close to realistic ones.

If we consider the idea to start from a real object and to proceed to a virtualization, we can compare both status of the object (see figure 3). Once the object virtualized, it is called a digital mock-up or an artifact; however, if the real object is conserved or repaired, it becomes also an artifact as it is not the same as the original object. The main differences are that visualization of a virtual object can be adapted to the public targeted:
- The scale of the virtual mock-up can vary from a macroscopic view to a microscopic view detailing its integration in a social-economical context (see the complete plant) to a functional precision [10].
- Dynamic analysis can be done by changing colours, or making transparency or cross sections so as to highlight the different components [11]
- Moreover, the main difference is about the visualization of the involved knowledge: textual annotations are laid near the real object; they give history, description and must be a synthesis. On the contrary, the virtual object proposes virtual annotations that could be texts, images, videos... the visitor can choose the level of detail he wants to explore,
- ...

3.2 A global methodology for virtualization

Before designing a virtual model, it is necessary to capitalize the necessary information. External knowledge has to be extracted as explained before and internal knowledge also. As detailed in Figure 1, the source of information which is the most important is obviously the object itself if it still exists. Consequently, picking up information on the object or its components gives more authenticity than extrapolating a drawing.

As seen in the part before, tools and methods from engineering sciences can give solution for this new kind of capitalization. Issued from the industrial engineering, the digital chain can be defined as per figure 4:

In the following part of this communication, we will concentrate on the first step of the digital chain process: the object digitalization. Details of the global process can be found in other communications [12].
4 3D DIGITALIZATION

Answering to the problematic of patrimonial object digitalization, we give a state of the art of the different technologies than can be found on the market or new technologies issued from fundamental research that will emerge in the near future.

We distinguish active systems and passive systems. The main difference is due to the technology used: emitting or not a light beam. Moreover, we also distinguish the system with contacts and without contact. As explained later in the communication, as we usually work with old objects, contact can be sometimes impossible or even forbidden.

4.1 Systems with physical contacts
They are the basic measuring instruments that are used since a long time:
- decameter,
- slide caliper,
- micrometer calliper,
- ...

They are also many mechanical palpation systems that are nearly automatic and are usually combined with a canned jib for controlled by a computer. Some of them are named TMM for Three-dimensional Measurement Machines. The most important difficulty is that the object that has to be measured has to be brought in the laboratory as those measurement systems are usually not movable. Moreover, they need many settings in order to be efficient and measurement is very slow. However, they can be effectives on large object: from 0.5 m³ to 115 m³.

4.2 Passive systems without contact
Usually used for graphical design, those systems are passive without contact since they capture information with photographic systems or stereoscopic systems. The acquisition tools are cameras and movie cameras.

Photographic systems allow building rapidly 3D models thanks to high definition numerical photos. The process associated is:
1. detecting common points between photography’s,
2. automatic distance calculations and 3D wireframe modelisation,
3. textures application using photography definition,
4. automatic virtual camera or virtual video camera positioning.

But it is necessary to precise that model precision depends on the cameras definition: more the cameras are accurate, more the model will be accurate.

4.3 Active systems without contact
Active systems without contact are technologies that generate short waves for measuring; for example: the laser. According to the object size to be digitized, there are various solutions:
- “desktop” laser scan: box containing the scanner. accuracy = 0.1 mm. It is suitable for only small size objects,
- TMM laser radar. High speed, high accuracy,
- 3D scanner laser. For example from Minolta. They are the most popular and are used for medicine, industrial engineering, archaeology...
- X-ray tomographic systems,
- Interferometer with optic fiber,
- Optic measure system,
- …

4.4 Classification
The technology that will be used depends on the dimensions to be acquired (...<1m<...<10m<...<60m<...), on the desired accuracy, the acquisition time available and the possibility to handle/move the object. Consequently, dealing with digitalization of patrimonial object, it will be advisable to combine the technologies (active/passive systems with/without contact) for optimizing the acquisition chain (example: without contact due to major degradation state).

The table shown on figure 5 compares the different technologies. Notice that digitalisation systems like interferometer or optic systems are not mentioned: they are still at a research state.

The last line of the table matches to the numbers of handling that have to be done in order to get the whole 3D model. Indeed, if only one point of view is considered, it will return only a stereographic view. Consequently, it is necessary to combine various points of view and/or various kinds of scanners. For instance, during the conference Computer Aided-Design-Manufacturing & Measurement Integration, Boeing presented a multiple-scanner digitalization system which is used for controlling the wings dimensions [13].

In order to be used taking into consideration the object conditions and what can be done or not with the patrimonial object, we establish a decision tree. Based on criteria, it helps to find the better solution for digitalizing the object within the time available, the precision needed...

They are two kinds of criteria:
- The operability factors that result from the technology to be used,
- And the data related to the object state.

The main factors due to the operability possibilities are:
- Measure relevance: firstly, it is necessary to clarify if it is necessary to digitalise the whole object. For example, in case of a crane, it will be a waste of time to capture all the girders as they are identical,
- The object being / the object full-scale: if the object is incomplete or does not exist, missing parts will be designed taking into account the knowledge of the designer and the external knowledge and know-how,
- Palpation possibility on the object,
- Relocating possibility of the object,
- Radiation exposure possibility: technologies used various wave lengths (infra-red, visible, X-ray...); sometimes, due to its degradation state, the object could not support specific wave lengths.
<table>
<thead>
<tr>
<th>Technology</th>
<th>With contact</th>
<th>Without contact</th>
<th>Active systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Passive systems</td>
<td>Active systems</td>
<td></td>
</tr>
<tr>
<td>Society / laser type</td>
<td>Measurement tools</td>
<td>Palpation</td>
<td>photo</td>
</tr>
<tr>
<td>... &lt; 1 m³</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1 m³ &lt; ... &lt; 10 m³</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>10 m³ &lt; ... &lt; 60 m³</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>60 m³ &lt; ...</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Maximum accuracy</td>
<td>1 micron</td>
<td>1 micron</td>
<td>photo</td>
</tr>
<tr>
<td>Acquisition speed</td>
<td>manual</td>
<td>slow</td>
<td>Time to take a photo</td>
</tr>
<tr>
<td>Number of manipulations to get a 3D model</td>
<td>Multiples</td>
<td>1 (automatic)</td>
<td>Many</td>
</tr>
</tbody>
</table>

**Fig. 5 Synthesis of the different technologies used for scanning objects**
TMM laboratory, size = 115 m³, precision = ½ µm

Volumic lased, precision = 0.1 mm, limited size

Direct modelisation

Measure relevance

Object full-scale being

Use context is known

Slide caliper, low speed, µ precision, every kind of matter, surface, size

Surface treatment authorized

Relocating

Palpation

Laser radar MMT without contact, distance between object and laser = 60, 1000pts/s, precision = 16 to 240 µm

Decameter, low speed, medium precision, every kind of matter, surface, size

Micrometer Caliper, idem decameter with a precision of few microns

Accessibility

CMM type krypton, size = 17 m³, precision = 40 µm, every kind of matter and surface, radiation exposure without contact

ATOS, size = 2 to 20 m, high speed capture, without contact

Radiation exposure different than visible

Photographic systems

X-ray, small size, necessity to move the object

Fig. 7 The decision tree for choosing the best digitalisation practice
Departure data issued from the object itself and characterizing it can be:
- The object material,
- Accessibility: sometimes, measures have to be done from point of view that are not accessible or even inside the object,
- The size of the object and the volume that has to be digitalized,
- Kinematics digitalisation: willingness to capture the working state,
- Digitalisation time: when many points have to be captured, some methods have to be prohibited,
- The accuracy: it interacts directly with the digitalisation time and the finality(ies) of the digitalisation,
- Handicraft or industrial object: an object issued from the domestic system need more points for being defined as all parts are not identical.

For example, linking various factors like digitalisation time, size, handicraftly... if we would like to digitalise a chair, it is necessary to wonder about the relevance to capture the entire geometric definition of the chair? Only remarkable points have to be considered: then, lines can be drawn between those points and next surfaces and volumes can be designed.

![Diagram of chair design using a cloud of points](attachment://chair_design.png)

**Fig. 6 Chair design using a cloud of points**

The figure 7 sums up all the tools explained previously and the way to choose the optimum technology. All digitalisation tools explained or developed previously are not mentioned but the main solutions are proposed. The circles are questions that must be asked; the arrow is...
green if the answer is Yes and red if the answer is No. However, please note that the method found by the decision tree may not be the only one but it is probably the best one to use. If another strategy is chosen, it will result in loosing cost, accuracy, efficiency or acquisition speed.

5. EXAMPLES

In this part, two examples we experienced are presented. They have been developed by our research team and our collaborators:

- Musée des Marais Salants de Batz-sur-Mer, Salt Museum, France
- Musée de l’Imprimerie de Nantes, Printing Machine Museum, France
- Morel Mapping Workshop, Architecture Digitalisation Entreprise, France
- IUT Carquefou, Mechanical Technician School, France

5.1 3D digitalisation for scholar learning

This project has been developed with an educational partnership: studying an old technical object allows obtaining new technical culture. This pedagogical interest can also be associated to a second objective: learning how to use CAD tools. The projects are realised by group of 3 or 4 students. Their mission consists in producing functional digital mock-ups of old printing machines. As those machines still exist and are fully operating, students can better understand how it works… but only with an external overview [14]. Indeed, old machine are very complex as they usually use one mechanical input for multiples output:

- Nowadays, for creating one movement, we generally use one motor; control is achieved by automatism, electronic or computerized; if multiples outputs are needed, we use as many motors as necessary.
- In the past, it was different. The main input power is furnished by human force or by a steam engine; ordinarily, the movement produced is a rotation. Next, they are many mechanisms that are totally desynchronised in order to achieve the different necessary output: coupling rods, wheel rods, many adjustments… The machines are very complicated and need to be studied in details for understanding the global operation.

The project presented in this example is a printing machine built by Henry Voirin. It was put into service in 1890 and finished its use life in 1985. The press was employed for printing posters for the French company NAZE. The technology is called cylinder stopping machine. This typographical press uses surround characters coating with a small layer of ink.
The press is semi-automatic as a steam engine and later an electrical motor is used for producing a uniform rotating movement. But two operators are also required for aligning and taking off the sheets.

The CAD model is made of approximately 615 components and more than 50 connections. Figure 9 presents the kinematics sketch that first has to be done in order to have a better understanding of the operation.

During their work, students have faced a problem with an actuating cam. Located at the beginning of the kinematics chain, this component is fundamental for succeeding in the simulation process. Although they were authorized to disassemble some elements, the cam was impossible to get out. Moreover, this component owns a special edge and classical measurement tools were inefficient. 3D digitalisation tool was then the solution that has been adopted.
Operability factors:
- **Measure relevance**: capital
- **The object full-scale**: yes
- **Palpation possibility**: yes
- **Relocating possibility**: no
- **Radiation exposure possibility**: all kind of wave lengths.

Data object:
- **Object material**: steel, lubricated and with major reflection but spray can be applied
- **Accessibility**: rather difficult as the component is inside the machine, the digitalisation system has to be small and easily handled
- **Size of the object**: less than 1 m³
- **Kinematics digitalisation**: no
- **Digitalisation time**: limited and has to be done as quickly as possible as the student project was nearly finished
- **Accuracy**: only the edge of the component is required
- **Handicraft or industrial object**: industrial

Consequently, in order to satisfy all the requirements, a new technology has been tested: the Handyscan from the Company Creaform [15]. Based on a Canadian patent, this tool allows digitalizing an object for obtaining a cloud of points. The scanner is self-positioning in 3D space thanks to reflecting targets. It is possible to scan many times the same point for optimizing its position. The precision is about 3/10 mm but it is mainly depending of the object volume that has to be digitalized. This technique is without contact and can not destroy the object as the laser emitted is visible by human.

![Image of the Handyscan and the cam](image)

**Fig. 10** On the left, the cam in white and the on right, the Handyscan
5.2 3D digitalisation for heritage conservation

In 1984, the “Musée des Marais Salants” (Salt-Water Museum) opened in Batz-sur-Mer in France. It is one of the first Arts and Popular Traditions Museums of West of France. Since 1987, Museum curators are faced with the lack of spaces; searching for new buildings, they found an architectural unit: it is an industrial building containing one of the last salt laundries of Bretagne, France. The first step consisted in acquiring the building, studying the feasibility for a possible extension of the Museum…

The washing machine is stored in the “Magasins de la Croix de Paix”. This warehouse was built in 1882 by Pierre Deniel for sheltering salt stocks. In 1886, it created a company for refining salt. In 1898, the farmer changed: Jean-Baptiste Bertrand succeeded. In 1914, he built a 750 m² building for housing and processing 6 000 tons of salt per year.

Washing sea salt process target is to eliminate soil particles and then, by mixing it with a saturated solution of salt. The device used is made of 3 trays provided with worms also called Archimedes screws [16].
The machine is in a so advanced state of degradation that it cannot operate. For succeeding in the understanding of the laundry operation, it was necessary:
- to consult the scientific reviews from the beginning of the 20th century,
- to rummage in the oldest libraries and archives,
- to ask questions to the previous workers,
- to analyse historian work about washing salt [17].

![Fig. 13 Photography of the salt washing machine in 2005](image)

At first, the machine and its shed have been studied and contextualized. Architectural drawings have been done by curators. They produced a statement of the object at a determined date.

![Fig. 14 Architectural drawings](image)

Later, in order to have a more precise artwork, it has been decided to digitalize the washing machine and its close industrial building.

Operability factors:
- **Measure relevance**: capital for immortalizing the object as it destroys itself more and more everyday
- **The object full-scale**: yes
- **Palpation possibility**: impossible
- **Relocating possibility**: impossible
- **Radiation exposure possibility**: all kind of wavelengths but not too hard for not destroying the wood.

Data object:
- **Object material**: not reflecting at all but not in good conditions
- **Accessibility**: some components hide some other ones; moreover, walls preclude some point of view
- **Size of the object**: approximately 120 m³
- **Kinematics digitalisation**: no
- **Digitalisation time**: unlimited in a short time but digitalisation has to be done quickly as the machine condition becomes worse every day
- **Accuracy**: linked with the handicraft status of the object
- **Handicraft or industrial object**: handicraft, impossible to copy and paste components, the global machine has to be digitalized.

Consequently, the only solution that can be used is a laser system. The digitalization was carried out thanks to a Leica scanner: laser Cyrax 2500. It is possible to obtain 1 point every 1 mm from a distance of 100 meters. In this case, a better precision is get as the scanner must be at a maximum of 10 meters far from the machine. The laser scans the surface to be digitalized, any reflecting material is returned towards its original emission point. Then, it is possible to calculate the time between emission/reception and determinate the 3D position of the point.

![Fig. 15 Cloud of points](image)

Once the cloud of points obtained, several solutions exist for using data: export the point to a CAD software, point-to-point direct measurement, automatic geometry rebuilding… Rebuilding the geometry can be carried out in an automatic way by pattern recognition. This solution is particularly adapted in the case of standard elements like cubes, tubes or simple surfaces (wing of car…). However, in the case of the washing machine, this solution was not possible due to the advanced state of the object degradation, which would have distorted the automatic form recognition. Consequently, the architect who realized the digitalisation computerized the points in order to obtain 2D drawings that have been controlled by the Museum curators.
Obviously, interpretations were necessary for validating the 2D drawings. However, next step that consisted in designing with 3D CAD software the machine, it had demonstrated that they were some problems with the drawings. Consequently, if it was proposed to build a new washing machine using the old technology, the craftsman would have difficulties and a re-design is indispensable.

6. CONCLUSION
In this communication, we are giving details of our research subject dealing with the conservation of the scientific and technical heritage. Focusing upon old objects such as industrial machines, our proposal is to virtualize them for a better communication of its knowledge.
At the beginning of the process, knowledge capitalisation is necessary: the context and obviously the artefact itself. In order to respect patrimony, 3D scanning technologies have to be selected and handled carefully. The decision tree can help to choose the optimum solution.
for digitalizing the object thanks to a good identification of the operability factors and the object characteristics.
Moreover, performance and diversity technologies are being developed everyday and, may be, one day, an innovative solution will be found being fully adapted for any kind of object: decametres, callipers… will disappear?

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