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# Towards Adaptive Manufacturing Systems - Knowledge and Knowledge Management Systems

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## 1. Introduction

Today the changes in the environment, be those business related or manufacturing, are both frequent and rapid. Industry has talked about the adaptation to meet the changes over a decade. Adaptation as a word has gained quite a reputation. Adaptation is expected in design of products and processes and in the realization of processes. The adaptation in the field of manufacturing sector is commonly understood as operational flexibility and reaction speed to the changes and/or opportunities. However, in order to achieve the required level of adaptability a company must be able to learn. Learning is achieved through gaining and understanding feedback of a change: its quantity and direction. Gaining and understanding the feedback a company must be able to compare the past status to the new status of actions. Unfortunately, the knowledge of neither the past nor the present is in computer interpretable and comparable form. Thus, the achieved and/or imagined flexibility is slightly above non-existent in reality.

This chapter discusses the possibilities of a modular and more transparent knowledge<sup>1</sup> management concept that provides means for representing and capturing needed information as feasible as possible while understanding that it is also the software systems that need to adapt to the changes along the physical production systems. The research approach discussed here aims to introduce new ideas for the companies knowledge management and process control by facilitating the move from technology based solutions to configurable systems and processes where the digital models and modular knowledge management systems can be configured based on needs - not based on closed legacy systems. The case implementation chosen here to illustrate this approach divides the knowledge management system into three separate layers: data storing system, semantic operation logic (the knowledge representation) and services that utilize the commonly available knowledge. The modular approach in

<sup>1</sup> In the knowledge management literature, three levels of knowledge - data, information and knowledge - are commonly distinguished. Awad and Ghaziri (2004) define data as unstructured facts, which in IT terms are usually considered as just raw bits, bytes, or characters. Information is structured data and attributes which can be communicated, but which may only have meaning locked inside proprietary software. Knowledge is seen as information that has meaning for more than just one actor and it can be used to achieve results.

ICT allows also software vendors to enhance their production to be more modular and configurable thus allowing the service oriented operation model to be realized. Once the storing method is separated from the logic and services, the new concepts can emerge. It is seen also that the vendors can make new business opportunities based on modular system solutions and configuration of those instead of highly tailored solutions which cannot be re-used later on.

The chapter is structured as following: the section 2 will illustrate the challenges industrial world is facing today. Section 3 summarizes the state of the art in field of knowledge modeling. Section 4 outlines needs for modularity in systems and introduces one possible solution candidate. Section 5 introduces a case implementation. Section 6 concludes the chapter and section 7 discusses about the challenges and future trends.

## **2. Set of challenges for the new decade**

### **2.1 From simple to complex operation environment**

For society to sustain and prosper, it needs along with societal, structural and organizational values a steady flow of income. For most of societies manufacturing has been and still is one of the biggest source of income. However, global competition has changed the nature of European manufacturing paradigms in past decades, see Figure 1. A turbulent production environment, short product life-cycles, and frequent introduction of new products require more adaptive systems that can rapidly respond to required changes whether or not the changes are based on product design changes or changes in the production itself. However, the technological leap in the mid 20th century, provided the means to venture towards more capable systems with very highly performing components. Today the acute problem is to take full advantage of their specific capabilities. These new systems, called complex systems, are no longer reducible to simple systems like complicated ones described by Descartes, Cotsaftis (2009).

Technical developments in recent years have produced stand-alone systems where high performance is routinely reached. This solid background has allowed the extension of these systems into networks of components, which are combined from very heterogenous elements, each in charge of only a part of the holistic action of the system. As the systems are process oriented instead of knowledge oriented systems, the interaction between tasks cannot be modeled, thus the effect of single interactions and relationships cannot be represented in the full systems scale. The types of interactions are changing into a complex network of possibilities within certain limits instead of a steady and predefined process flow. This situation is relatively new and causes pressures to define the role of intended interaction. According to Chavalarias et al (2006), there is no doubt that one of the main characteristics of complex and adaptive production platforms in the future will be the ever- increasing utilization of ICT. However, while the industrial world has seen the possible advantages, the implementations fall short as a result of the required changes to the whole production paradigm, going from preplanned hierarchical systems to adaptive and self-organizing complex systems, Chavalarias et al (2006) and Cotsaftis (2009).

Chavalarias et al (2006) stated that complex systems are described as the new scientific frontier which has been advancing in the past decades with the advance of modern technology and the

increasing interest towards natural systems’ behavior. The main idea of the science in complex systems is to develop through a constant process of reconstructing models from constantly improving data. The characteristics of a multiple-component systems is to evolve and adapt due to internal and external dynamic interactions. The system keeps becoming a different system. Simultaneously, the connection between the system and its surroundings evolves as well. When multiple-component system is manipulated it reacts via feedback, with the manipulator and complex system inevitably becoming entangled.

Paradigm	Craft Production	Mass Production	Flexible Production	Mass Customization and Personalization	Open Complex and Adaptive Production Systems
Paradigm started	~1850	1913	~1980	2000	2020
Society needs	Customized Products	Low cost products	Variety of products	Customized products	Customized on-demand products
Market	Very small volume per product	Steady demand	Smaller volume per product	Global manufacturing and fluctuating demand	Global manufacturing and fluctuating demand
Business Model	Pull Sell-design-make-assemble	Push design-make-assemble-sell	Push-Pull design-make-sell-assemble	Pull design-sell-make-assemble	Pull design-sell-make-assemble
Technology Enabler	Electricity	Interchangeable parts	Computers	Information technology	Information and communication technology
Process Enabler	Machine tools	Moving assembly line	Flexible Manufacturing Systems, robots	Reconfigurable Manufacturing System	Self-organizing agents

Fig. 1. Paradigm shift, adapted and modified from ManuFuture Roadmap published by European Commission (2003)

In complex systems, reconstruction is searching for a model that can be programmed as a computer simulation that reproduces the observed data ‘well’. The ideal of predicting the multi-level dynamics of complex systems can only be done in terms of probability distributions, i.e. under non- deterministic formalisms. An important challenge is, contrary to classical systems studies, the great difficulty in predicting the future behavior from the initial state as by their possible interactions between system components is shielding their specific individual features. In this sense, reconstruction is the inverse problem of simulation. This naturally indicates that the complex system cannot be understood as deterministic system, since the predictions from Complex Systems Science do not say what will happen, but what can happen, Valckenaers et al (1994), Chavalarias et al (2006), Cotsaftis (2009) and Lanz (2010).

In general, complex systems have many autonomous units (holons, agents, actors, individuals) with adaptive capabilities (evolution, learning, etc), and show important emergent phenomena that cannot be derived in any simple way from knowledge of their components alone. Yet one of the greatest challenges in building a science of such systems is precisely to understand this link - how micro level properties determine or at least influence properties on the macro level. The current lack of understanding presents a huge obstacle in designing systems with specified behavior regarding interactions and adaptive features, so as to achieve a targeted behavior from the whole, Chavalarias et al (2006).

Due to the complexity of the system behavior and the lack of tangible and implementable research results on how complex systems theory can bring revenue to a company; implementations at the moment are scarce and acceptance varies. In order to meet the new requirements set by the evolving environment several new manufacturing paradigms have been introduced, which follow characteristics of natural systems. These paradigms are:

- **Bionic Manufacturing System (BMS):** The BMS investigates biological systems and proposes concepts for future manufacturing systems. A biological system includes autonomous and spontaneous behavior and social harmony within hierarchically ordered relationships. Cells as an example are basic units, which comprises all other parts of a biological system and can have different capabilities from each other, and are capable of multiple operations. In such structures, each layer in the hierarchy supports and is supported by the adjacent layers. The components, including the part, communicate and inform each other of the decisions, Tharumarajah et al. (1996) and Ueda et al. (1997).
- **Fractal Factory (FF):** The concept of a fractal factory proposes a manufacturing company composed of small components or fractal entities. These entities can be described by specific internal features of the fractals. The first feature is self-organization that implies freedom for the fractals in organizing and executing tasks. The fractal components can choose their own methods of problem solving including self-optimization that takes care of process improvements. The second feature is dynamics where the fractals can adapt to influences from the environment without a formal organization structure. The third feature is self-similarity understood as similarity of goals among the fractals to conform the objectives in each unit Tharumarajah et al. (1996) .
- **Holonic Manufacturing System (HMS):** The core of HMS is derived from the principles behind the term 'holon'. The term holon means something that is at the same time a whole and a part of some greater whole Koestler (1968). The model of integrated manufacturing systems consists of manufacturing system entities and related domains, the structure of individual manufacturing entities, and the structuring levels of the entities. A manufacturing system is, at the same time, part of a bigger system and a system consisting of subsystems. Each of the entities possesses self-description and capability for self-organization and communication, Valckenaers et al (1994) and Salminen et al (2009).

## 2.2 The meaning of knowledge

It is said that the world is surrounded by knowledge. Knowledge is saved into knowledge-bases and managed by knowledge management systems is something what has been stated over and over again. However, today, no matter what the vendor flyers express with colorful pictures and highly illustrative arrows, knowledge - as computers can understand it and reason with it - is not saved. The majority of the research and design effort is never captured or re-used. The interpretation of, for example a technical drawing is entirely based on the human perception and this perception may vary. *"The meaning of knowledge is not captured and therefore not utilized as it has been intended."*

The need today is the capability for rapid adaptation to the changes in environment based on the previously acquired knowledge. However, the challenge is precisely the input knowledge or to be more accurate: the lack of it. In a large-scale company there can be up to hundreds of different design support systems, versions, and ad-hoc applications, which are used to create

the information of the current product, process, and/or production systems. The majority of systems are using proprietary data structures and vaguely described semantics. This leads to challenges in information sharing since none of those are truly able to share data beyond geometrical visualizations. The design knowledge - the design intention - if even created, remains locked inside the authoring system, Ray (2004), Lanz (2010), Jarvenpaa et al. (2010), Lohse (2006) and Iria (2009).

### 3. The state of the art

#### 3.1 Data modeling

As product, process and manufacturing system design have become more and more knowledge-intensive and collaborative, the need for computational frameworks to support much needed interoperability is critical. Academia and industrial world together have provided multiple different standards for product, process and resource models ranging from conceptual models to very formal representations. However, there are some serious shortcomings in the current representations:

- Firstly, none of these can represent the needs of the industry, not even industrial sector as whole.
- Secondly these standards do not form a knowledge architecture due to the missing critical parts (such as life-cycle information of products, processes and factory systems, history of past events and occurrences).
- Thirdly, there does not exist a study that would outline the overlapping between these standards, Lanz et al. (2010).

Table 1 summarizes several different languages to represent data models that exist today. The list is not complete, nor it is intend to be, but it will summarize examples of standards, de facto standards and other models that are used today by industry and academia.

There have been three main approaches used to create a knowledge exchange infrastructure. They are a "point-to-point" customized solution, where dedicated interfaces are created between the design tools; a "one size fits all" solution decided by the original equipment manufacturer (OEM)'s proprietary interface for design and planning and knowledge exchange between parties; and the third solution is the a "neutral and open reference architecture" based on published standards. The first approach is expensive and time-consuming for the OEM, while the second option is very cost-efficient for the OEM, but expensive for partners who are working with several OEMs. The third option has never been fully implemented, Ray (2004), Lanz (2010) and Lohse (2006).

#### 3.2 Knowledge capture

Second large problem area is the knowledge capturing. Currently there are very few systems that can be called knowledge capturing systems. By the definition information becomes knowledge, once other parties exist, which can understand the meaning of the information and can use it for their own purposes. In large scale organizations, data regarding activities and tasks are routinely stored in an unstructured manner, in the form of images and natural language used in e-mails, word-processed documents, spreadsheets and presentations. Over

LANGUAGE/STANDARD	USED IN PROJECTS AND STANDARDS	DESCRIPTION AND USE
EXPRESS	Standard for the Exchange of Product model data (ISO 10303 STEP), Open Assembly Model (OAM), Core Product Model (CPM), Krima et al (2009)	Defining the connections between the artifacts
CommonCADs	EUPASS Ontology, Lohse (2006)	Definition of interdependencies between classes
Web Ontology Language, Description Logics (OWL DL)/ Resource Description Framework (RDF)	Core Ontology Lanz (2010), ontoSTEP, Krima et al (2009)	Definition of interdependencies between classes and artifacts
First Order Logic (FOL)	Core Ontology, Lanz (2010)	Definition of interdependencies between classes
Common Logic Interchange Format (CLIF)	Process Specification language (PSL)	Describing what actually happens when a process specification executes and for writing constraints on processes, Bock & Gruninger (2005).
eXtensive Mark-up Language (XML)	Core Manufacturing Simulation Data (CMSD)	Used for the exchange manufacturing resource data
Automation ML	Knowledge Integration Framework ROSETTA (2010)	Representation Language of entities ROSETTA (2010)
Pabadis Promise Product and Production Process Description Language (P5DL)	OWL based language in FP6 Pabadis'Promise (2006)	P5DL used for description of products (as STEP) with their commercial and control relevant data and their necessary control applications and description of manufacturing processes with their hosting resources and necessary control functions, FP6 Pabadis'Promise (2006).

Table 1. Means for representing domain knowledge

time, large unstructured data repositories are formed, which preserve valuable information for the organization, if this information can ever be found or used.

Thus, a challenging research issue is to consider how information and knowledge is spread across numerous sources, and how it can be captured and retrieved in an efficient manner. Unfortunately, traditional information retrieval (IR) techniques not only tend to underperform on the kinds of domain-specific queries that are typically issued against these unstructured repositories, but they are also often inadequate, Iria (2009). The capturing of knowledge should start already from the creation of knowledge, where the engineer knows the meaning of the models and documents he/she is creating. This meaning should be captured in a form of computer readable format, such as a formal ontology, for further use.

### 3.3 Knowledge and meaning

According to DoHS (2008) increasing trend can be found from ongoing research in different domain contexts on using emerging technologies such as ontologies, semantics and semantic web (Web 2.0), to support the collaboration and interoperability. In recent years there have been a lot of activities concerning the domain and upper ontologies for manufacturing. As a result for the FP6 EUPASS project Lohse (2006) defined the connection between processes and resources for modular assembly systems. FP6 Pabadis'Promise (2006) project resulted in a manufacturing ontology (P2 ontology) and, reference architecture focusing on factory floor control.

Borgo & Leit (2007) developed the ADACOR ontology for distributed holon-based manufacturing focusing on processes and system interaction descriptions. ADACOR was later extended with an upper ontology Descriptive Ontology for Linguistic and Cognitive Engineering (DOLCE). Research done in the FP6 IP-PiSA project resulted an ontology, called Core Ontology, for connecting product, process and system domains under one reference model, Lanz (2010). The main goals these approaches generally try to achieve are: improved overall access to domain knowledge and additional information. However, none of these developed ontologies fully consider the needs above their narrow domain, Ray (2004), Lanz (2010), Jarvenpaa et al. (2010).

Ray (2004) introduced a roadmap from common models of data to self-integrating systems. The table 2 shows the 4 levels of representation. The table shows the logical steps for reaching first the creating of meaningful models (as in computational sense) to achieving finally systems that can autonomously exchange knowledge and operate based on shared knowledge.

According to the guidelines envisioned by Ray (2004), Lanz (2010) developed a common knowledge representation (KR) and semantics, called as Core Ontology, that allowed different design tools to interoperate across the design domains. The structure of the KR was formed on the basis of the requirements set by the knowledge management and integration challenges between different design tools, and the requirements set by the dynamic and open production environment. The developed model formalized the knowledge representation between product, process, and system domains utilizing fractal systems theory as a guideline. The surrounding system, be it the design environment or adaptive production system, can focus on the reasoning at different levels of abstraction, while the KR remained neutral for these

LEVELS OF REPRESENTATION	DESCRIPTION OF CHARACTERISTICS
Common Models of Data	In the lowest level the current state of the art, where the XML-based standards are utilized with relative ease within the IT sector, but not fully utilized in more conservative industry sectors.
Explicit and Formal Semantics	The second step, formal semantics, offers the generation of standardized representation that is formal enough to be parsed with computers.
Self-describing Systems	The third step is self-describing systems, where the systems can provide formal descriptions of their content and interfaces. This requires a formal semantic definition language that is rigorous enough to support logical inference.
Self-integrating Systems	The fourth level that Ray (2004) proposes is self-integrating systems. These systems are intelligent enough to be able to ask others for a description of their interfaces and, on the basis of the information thus acquired, adjust their own interfaces to be able to exchange information.

Table 2. The evolution of representational power towards formal semantics, and the systems integration capabilities that could follow (Ray, 2004)

reasoning procedures, but force the saved information to be consistent across the models. This approach differs from the traditional approaches by the fact that these tools are all utilizing already existing information as well as contributing specific information to the same model from different perspectives. The main objective of the developed KR was to achieve level two of the knowledge roadmap illustrated in the table 2. Other similar models exist, which utilize the complex nature of production systems. Most of these approaches are in the field of autonomous systems and control science.

4. Towards modular knowledge architecture for the dynamic environment

4.1 Understanding the Life-cycles of systems

All systems have their own life-cycles. In an open and complex operation environment the life-cycles play a very important role. The life-cycles that products can have are the most well-known life-cycle phases. These are such as in design, approved, in manufacturing, obsolete and such. These life-cycle phases represent the status of the design information.

The resource units also have their own specific life-cycle phases. These life-cycle phases describe the essential part of individual system units. Fore example, in the case of manufacturing resources the payload of a robot, accuracy of the tool and joints or tolerances do change over the life-cycle of the machine. It may happen that the capabilities of a system decline when it proceeds along its life-cycle. An example could be the capability for manufacturing certain surface with tight tolerances is possible when the machine is relatively new, but once the operating hours exceed a certain level the capability to reach the needed tolerances is no longer possible. Another example is the combined capability of an advanced manufacturing center and its operator. The machine may have dormant capabilities to

perform advanced operations, which can be obtained once the operator has achieved needed knowledge in this particular case. Now the combined system’s capabilities have increased.

In the case of modular knowledge architecture, ICT has also its own life-cycle. It is accepted from the start that the business field may change. When the change happens the ICT architecture must also adapt to the change. The change can happen also in the technological side when new technologies replace old ones. This means that some of the services may become obsolete and new services need to be added. In order to keep the architecture maintainable one solution is to offer independent service modules that operate over one information model without direct integration to the underlying databases.

4.2 Layers of operation

One of the approaches divides the knowledge management system into three separate layers: databases, semantic operation logic (the knowledge representation) and services that utilize commonly available knowledge. The modular approach in ICT allows also the software vendors to enhance their production to be more modular and configurable thus allowing the service oriented operation model to be realized. Once the storing method is extracted from the logic and services, the new concepts can emerge. It is also seen that vendors can make new business strategies based on new modular system solutions and configuration of those instead of highly tailored solutions, which cannot be re-used later on.

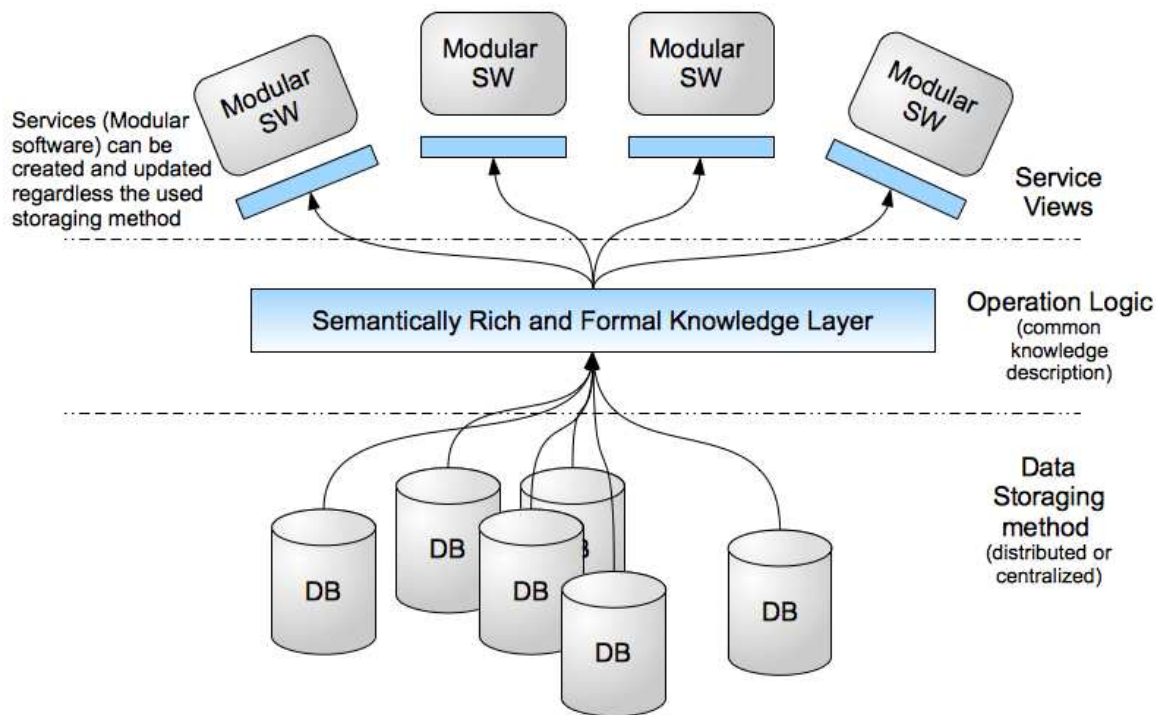


Fig. 2. Modular ICT

The ultimate goals in this particular research effort were to provide an information architecture, which allows different utilization of domain knowledge, while keeping the core information consistent and valid throughout the life-cycles of that particular set of information. The primary requirements that were defined together with industry are:

1. The model needs to represent the function of products and systems;
2. The model needs to connect different domains under one representation;
3. It must contain the history of changes applied to different instances;
4. The model must serve as an input source for automated information retrieval and reasoning in the traditional and in holon-based operation environment;
5. The model must be independent of the database implementation and services;
6. The model must allow as well as facilitate the generation of different services; and
7. The model must be extendable without disrupting the validity and consistency of the core domains.

5. Implementation of a modular ICT system

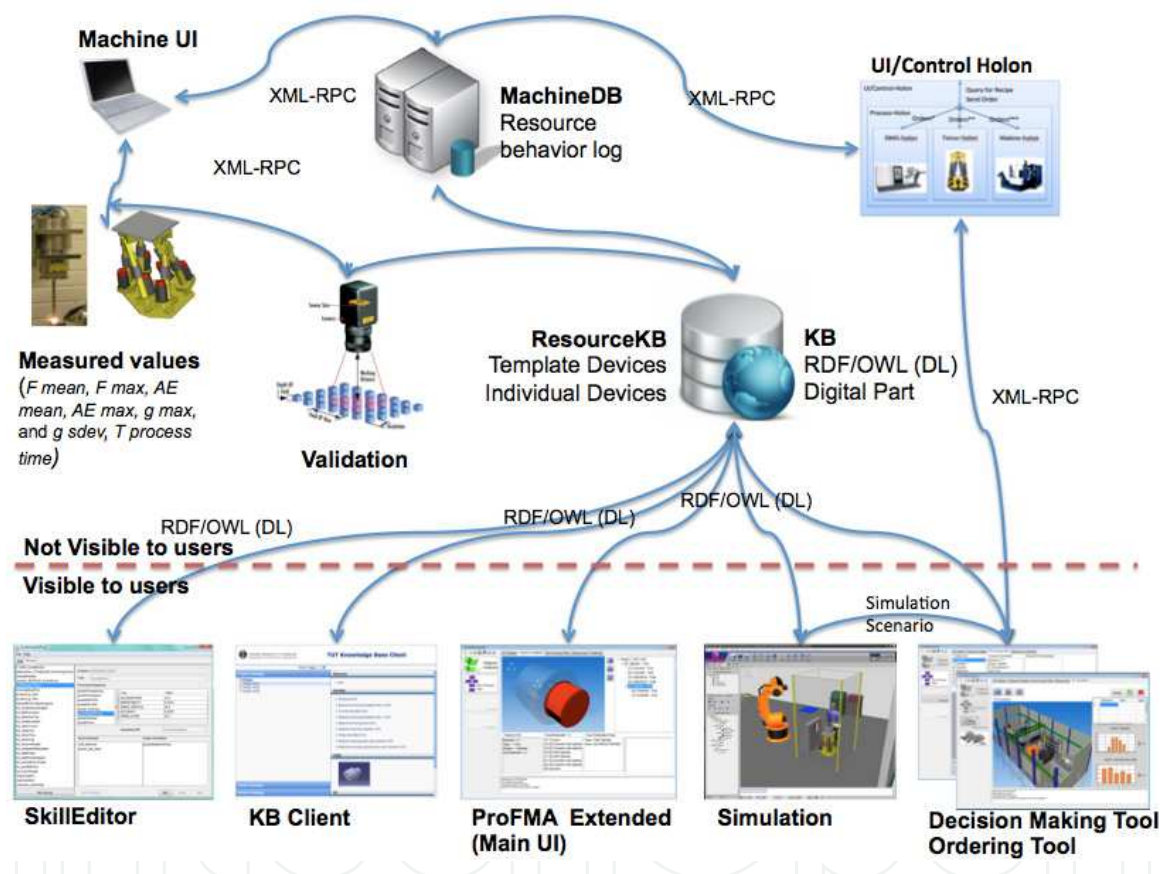


Fig. 3. implementation

The developed system, used here as an example, was based on the common knowledge representation and modular services would look as illustrated in figure 3. The clients contributing to the knowledge base are both commercial and university built existing systems and beta versions. Each of these tools requires specific domain related information and by processing the information they provide a set of services. However, the core of the system, the Knowledge Base (KB), needs to be extended to allow the capture and storing of semantically richer knowledge Lanz (2010) and Jarvenpaa et al. (2011).

The utilized knowledge representation (KR) can capture the meaning of classes via relationships that are defined between the classes. This technology allows semantic richness

to be embedded into the model. Several service providers can use the meaning of stored information for their own specialized purposes. The model is divided into three separate layers as illustrated in figure 2. By dividing the data reserves, operation logic and services into separate layers connected with interfaces the upgrading of layers becomes independent of each others. This allows services to be extended, replaced and modified throughout their life-cycles.

In this case study the whole system architecture, illustrated in figure 3 has several different interoperating software modules each providing one or two essential functions for the whole holonic manufacturing system. The architecture is designed in such way that each of the modules can be replaced with a new module if needed. The connection of the modules is mainly based on the shared information model, the Core Ontology, described in detail in Lanz (2010), Lanz et al. (2011) and in Jarvenpaa et al. (2011).

The tools in the environment are designed by keeping the modularization principles in mind. Each of the tools are contributing their specific information to the common information model. The tools provide one or two main functionalities to the software environment. The modular design of the software allows changes to be applied to the tools with minimum disturbances. For example the holon user interface (UI), which controls the actual production can be replaced with a commercial tool that provides queueing functionality for the system.

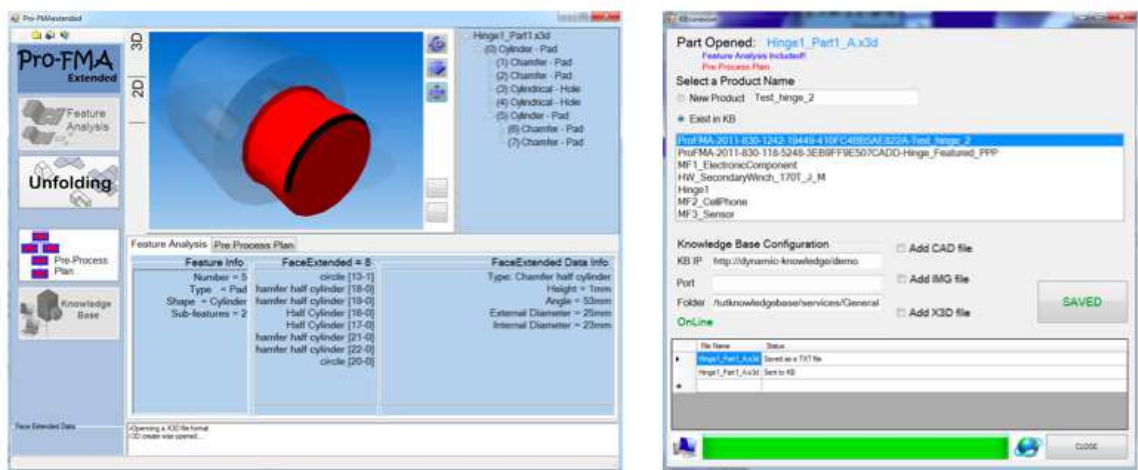


Fig. 4. Pro-FMA tool

The tools are:

**Content creation:** Pro-FMA illustrated in figure 4 is used to define the product requirements from the product model given in virtual reality modeling language (VRML) or eXtensive 3D (X3D) format. Product requirements are those product characteristics or features that require a set of processes for product to be assembled or manufactured. Features can be geometrical or non-geometrical by nature. These processes are executed by devices and combination of devices possessing adequate functional capabilities, Garcia et al. (2011).

**Context creation:** The Capability Editor, illustrated in figure 5, allows user to add devices to the ontology and assign them capabilities and capability parameters and enables creating associations between the capabilities. In other words it creates rules about which simple capabilities are needed to form combined capabilities, Jarvenpaa et al. (2011).

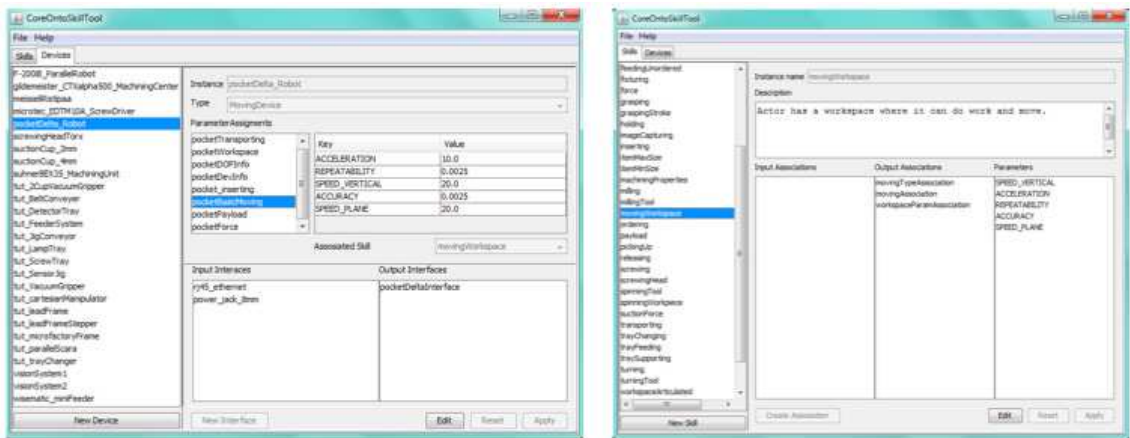


Fig. 5. Editor for Capabilities



Fig. 6. Decision Making and Ordering Tool

**Current implementation of the KB**

- Apache 2 web service engine,
- Jena semantic web framework
- Pellet reasoner, and
- Postgre database.
- Web services: XML/RPC
- RDF/OWL

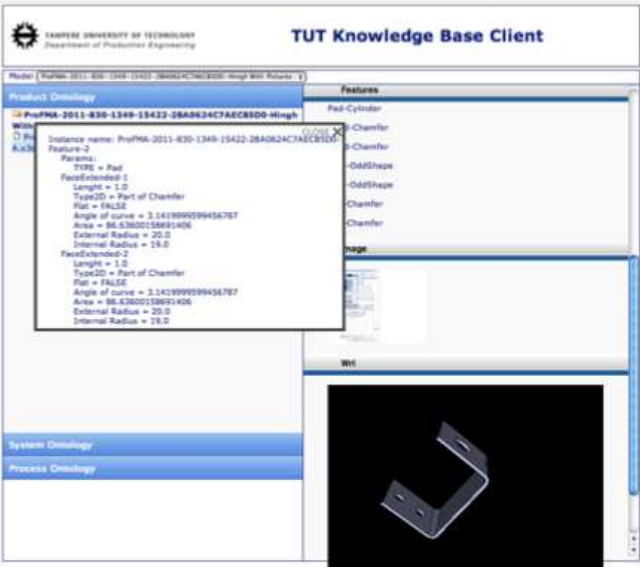
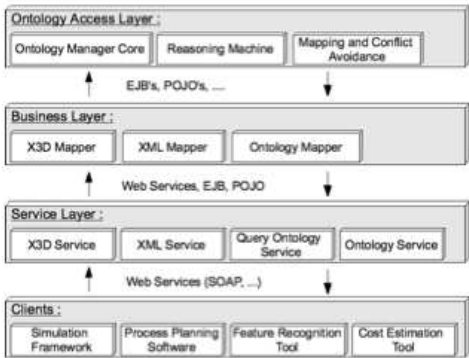


Fig. 7. Knowledge Base and Knowledge Base Web Client

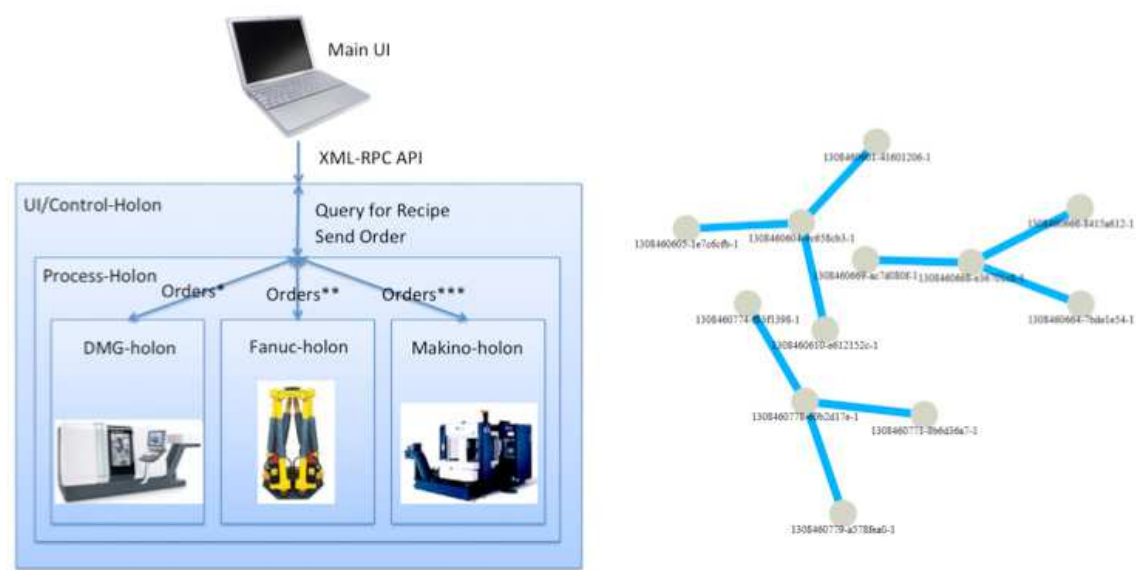


Fig. 8. Holonic control based on Kademlia, the right side of the figure shows the messages sent between holons

**Verification:** A simulation tool is used for creating the manufacturing or assembly scenarios. Since the environment is holonic by nature, it is accepted that the simulation only expresses possible solutions. The operation principle inside the simulation also follows holonic guidelines. This means that part or product is routed to the first available and capable cell.

**Ordering:** The Decision Making and Ordering Tool (DeMO tool), in figure 6, is used for setting up orders in this environment. The tool supports the viewing of the simulation as its minor function. The main function of the DeMO tool is to verify the connection to the factory floor and forward the orders to the holonic UI, Garcia et al. (2011).

**Common Knowledge Representation:** The KB and ResourceKB, shown in figure 7, store the information created by Pro-FMA, Capability Editor and DeMO tool. This system serves also as reference architecture, since it can handle closed models as references. The knowledge representation used in this case is based on OWL DL. The simulation model can be attached to product definition if needed. Similarly closed sub-programs and Computer-Aided-x (CAx) models can be associated with the part/product/resource description, Lanz (2010).

**Content Verification:** A web-based KB client, shown in figure 7 is used for human friendly information browsing. This tool serves as product data management (PDM) system’s web-based user interface (UI). The client allows only limited set of changes to be applied tot he ontology. These changes are for example a new name for a product, part or other instance. For more details, please see Lanz (2010).

**Operations Management:** The process flow and distribution of tasks to each manufacturing or assembly cell is done with the Control Holon, see figure 8. The control holon observes the status of the system and available capabilities of system units (manufacturing resources in this case). The manufacturing resources can enter to and leave from the network without disturbing the whole system. This holonic control system distributes the tasks to suitable and available cells or stations based on the capability requirements defined by Pro-FMA earlier.

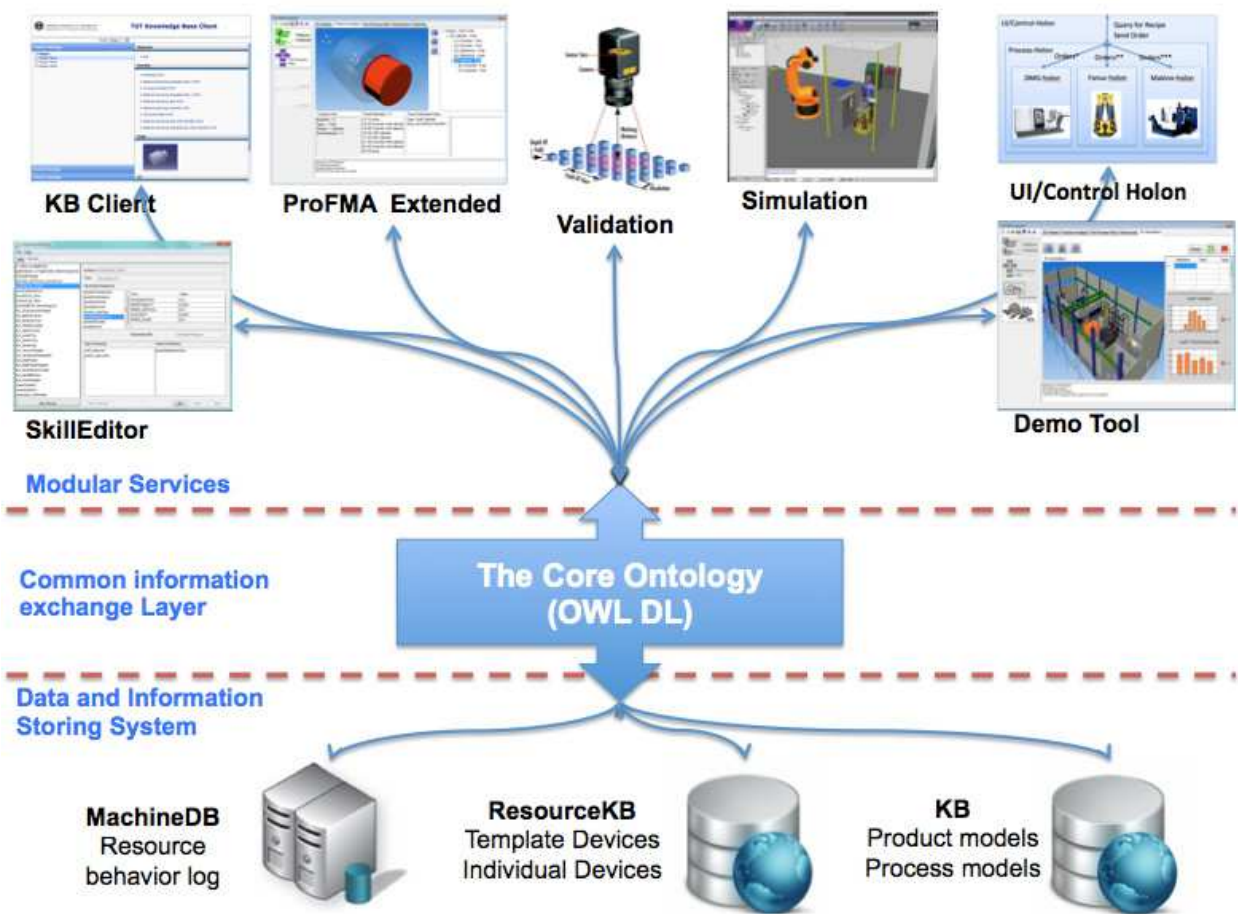


Fig. 9. The implementation is formed based on the modular ICT concept

The tools are divided into the layers described in previous chapter, see figure 2. The implemented environment, in figure 9, allows the addition of new services which can contribute and /or utilize already existing information, thus proving the modular ICT concept feasible for an adaptive, open and complex manufacturing environment. These tools constitute the necessary core for a modular system. There are additional services that could be added to this environment. These are traditional operation management module for production orchestration and machine vision based validation module. Both services are seen as extra for the core system.

6. Conclusion

Manufacturing after all is the backbone of each and every society, and in order for a society to be sustainable in long run the manufacturing has to be sustainable as well. From another point of view, manufacturing systems are shifting from being to becoming. This means that as the intelligence and cooperativeness advances the system will become a society where the rules, possibilities and constrains of a society as we know it will also apply. In order to achieve goals in the manufacturing society this research effort will contribute tremendous assets for securing the paradigm shift while keeping the manufacturing industry sustainable, flexible and adaptive. Without acceptance, further concept developments and implementation of the

open and complex system approach the industry will not meet the challenges of the evolving environment.

It is seen that one partial solution is to develop these kind of modular ICT architectures that support the evolution of systems. However, it is understood that there is a lot of developments and solutions needed, since the industry cannot adopt partial solutions. Industry will require a concept that allows several data sources to be combined under one coherent and valid representation that facilitate the design and utilization of intelligent services in open and dynamic operations environment.

This paper introduced the context and operation principles of a dynamic system, and what is needed to support this kind of system from the knowledge management perspective. The article emphasized the challenge of dynamic systems from the life-cycle perspective as well, since all of the system parts be those software or hardware have their specific life-cycle phase. The division of architecture does provide tremendous possibilities for service development in future. As a proof of concept one type of modular ICT architecture and its core tools were introduced.

These results introduced here can be utilized in other fields than manufacturing engineering as well. The field of constructed environment and urban development has already seen the potential of an open world system where the input can be delivered in formal representation and services can be created independently of each other.

## 7. Discussion

When discussing about the holonic concepts with different people in seminars, workshops and conferences, a common comment/question has been: "Holonic manufacturing systems were developed 20-30 years ago and they didn't work then. How could they work now?" Shortly put, the answer could be technological and methodological development of knowledge and information management. Reasoning needed in the holonic systems relies on information and knowledge. Even though the concept of holonic manufacturing has remained similar throughout the years, information technology has made huge leaps enabling the implementation of these concepts in a feasible way. The novel methods to manage and distribute knowledge, such as semantic web and web service technologies, as well as semantic knowledge management systems, have been paving the way for the successful implementation of holonic systems.

Another question, which often arises in discussions has been: "Why holons? What advantages we gain by implementing holonic architecture? The implementation seems to be a huge task." Holons are autonomous and self-describing entities having well defined interfaces and the ability to communicate and co-operate with other holons. The modularity and self-organization ability enables the holonic systems to be extendable and adaptable. New holons, be they software system modules, new manufacturing resources or human workers, can enter and leave the system without disturbing the operation of the whole system. Each holon, module, knows its own purpose and the inputs and outputs, making the operation more transparent. In a holonic system it is possible to make changes in individual modules without the need to change/re-program the whole system. Until recently the holonic paradigm has only been implemented to physical devices and immediate control architecture

of those. The design, operations management and supporting ICT systems have been ignored. However, as the ICT is expected to adapt to the changes in the production environment the holonic paradigm provides operation principles for this side as well.

Manufacturing is not the only domain, where the holonic paradigm could be applied. Actually, it could be applied almost anywhere, like in a medical and logistical domains. A good example can be found from city logistics. Cities, and their design, are not centrally controlled organized systems, but they are characterized by some level of chaos and the continuous threat of the chaos to expand to other operational areas. This chaos is controlled by hierarchical control systems where the control is coming from the top. From this viewpoint chaos is always considered as a negative element. This kind of systems need always be implemented as closed systems in order to prevent chaos.

The problem here is that innovations do not happen in order and harmony. The innovation always causes temporary chaos. Hierarchical control naturally strangles innovation. Therefore, what is needed is a control system where chaos is not a matter of crisis, but a normal event the system can handle in a flexible and efficient way. This kind of control system can be called as "chaordic system" (chaos + order). "Chaordic system" is self-organizing system which can always find a new equilibrium when the situation changes. The holonic control architecture can answer to the requirements of the "chaordic system". This idea has been presented to experts in the field of city logistics with very good feedback. The experts saw significant development potential for their business in holonic architecture in ICT and following the "open system" principles. However, all of this will be just theoretical discussion unless the surrounding ICT does support the change.

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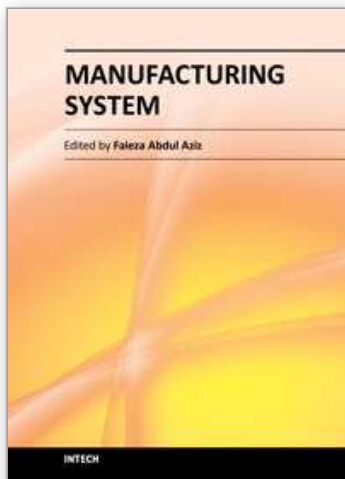
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