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VIEWPOINTS ON DIGITAL, VIRTUAL, AND REAL ASPECTS OF MANUFACTURING SYSTEMS

Hasse Nylund
Department of Production Engineering
Tampere University of Technology
Tampere, Finland
hasse.nylund@tut.fi

Paul Andersson
Department of Production Engineering
Tampere University of Technology
Tampere, Finland
paul.andersson@tut.fi

ABSTRACT

Information and Communication Technology (ICT) plays a key role in improving the efficiency of manufacturing activities. This paper proposes an approach where a manufacturing system is logically divided into digital, virtual, and real existences. The digital and virtual parts present the ICT view where the digital part includes the information and knowledge while the virtual part corresponds to computer models and simulations. Both have their roles in improving the manufacturing activities happening in the real part i.e. producing products and services to customers. These issues are discussed from theoretical aspects explaining structures of manufacturing entities and systems as well as manufacturing activities and improvement. The issues are also explained and demonstrated in a context of an academic research environment.

KEYWORDS

Manufacturing, Digital, Virtual, Improvement

1. INTRODUCTION

In this paper digital, virtual, and real characteristics of manufacturing systems are discussed. The main idea is to justify the division of the computer world into digital and virtual existences although existing in an integrated fashion. The digital part refers to the information and knowledge while the virtual part includes computer models and simulations. Both of the parts exist in multiple areas of overall management of manufacturing systems and, at the best, offer more efficient support for the decision making in different manufacturing activities.

The idea for the division derives partially from the concept of holons. Koestler (1989) introduced the term holon, which derives from the Greek word '*holos*', meaning a whole, and the suffix '*-on*', meaning a part. In other words, a holon is a whole system, and at the same time, it is part of a larger system. Valckenaers et al., (1994) initiated the concept of Holonic Manufacturing Systems (HMS). HMS describes a manufacturing system in terms of holons, autonomous and co-operative building blocks of manufacturing systems, capable of performing their own tasks independently, and to collaborate with each other to fulfil their common objectives. Additionally, in HMS, each holon consists internally from an information processing part and often a physical processing part (Van Brussel et al., 1998). In the division presented in this paper, the physical processing part corresponds to the real part and the information processing part is divided into the digital and virtual parts.

The division is discussed from different viewpoints, including:

- Describing the structures of manufacturing entities and systems.
- Discussing of the role of the division in manufacturing activities and improvement.

The theoretical issues are also presented in the context of an academic research environment, a piloting environment for current and future research topics, aiming to narrow the gap between the theoretical research issues and their implementation into industrial environments.

1.1. BACKGROUND

The research on digital and virtual manufacturing systems, factories, and enterprises has no commonly used definitions. However, they usually share the idea of managing the typically isolated and separate manufacturing activities as a whole by the means of Information and Communications Technology (ICT) (Nylund and Andersson, 2011). Typical examples, often found in the literature, are (see, for example: Bracht and Masurat, 2005; Maropoulos, 2003; Offodile and Abdel-Malek, 2002; Reiter, 2003; Souza et al., 2006):

- An integrated approach to improve product and production engineering technology.
- Computer-aided tools for planning and analysing real manufacturing processes.
- A collection of new technologies, systems, and methods.

Kühn, (2006) describes the digital factory concept that offers an integrated approach to enhance the product and production engineering processes. Typical areas of the processes are, for example: product development and product lifecycle management; production process development and optimisation; factory and material flow design and improvement; and operative production planning and control.

Constantinescu and Westkämper (2010) have presented a reference model for factory engineering and design that is used as an integrated planning environment. The planning viewpoints are structured in four main clusters i.e. strategic, structure, and process planning as well as the planning of factory operation and use.

The digital and virtual aspects can also be divided into information and knowledge management as the digital view, and computer models and simulations as the virtual part. Examples of the application areas of the virtual part are:

- Computer-aided manufacturing (CAM), e.g. offline programming for virtual tool path generation to detect collisions, analyse material removal and optimise cycle times (Kühn, 2006).
- Visual interaction applications, e.g. virtual environments and 3D-motion simulations that offer realistic 3D graphics and animations to demonstrate different activities.
- Simulation for the reachability and sequences of operations as well as internal work cell layout and material handling design (Kühn, 2006).
- Discrete event simulation (DES) solutions including the need for and the quantity of equipment and personnel as well as evaluation of operational procedures and performance (Law and Kelton, 2000).
- DES can also be focused on traditional supply chain sales and delivery processes as well as to complex networked manufacturing activities, including logistical accuracy and delivery reliability of increasing product variety (Wiendahl and Lutz, 2002).

Effective knowledge management consists of four essential processes: creation, storage and retrieval, transfer, and application, which are dynamic and continuous phenomenon (Alavi and Leidner, 2001). Examples of the application areas of the digital part are:

- Email messages, Internet Relay Chat (IRC), Instant Messaging, message boards and discussion forums.
- More permanent information and knowledge derived from the informal discussions, stored in applications such as Wikipedia.
- Formally presented information systems, such as Enterprise Resource Planning (ERP), Product Data Management (PDM), and Product Lifecycle Management (PLM).

The total information and knowledge of a manufacturing system can be explained with explicit and tacit components (Nonaka and Takeuchi, 1995). The explicit part of the knowledge can be described precisely in a formal way and can be included as the digital part. The skills of humans are explained as the tacit dimension of knowledge, which, presented digitally, may lead to unclear situations and can be wrongly understood. The importance of the transformation from tacit to explicit knowledge has been recognized as one of the key priorities of knowledge presentation (Chryssolouris et al., 2008).

The division into digital, virtual, and real is intentionally missing the tacit dimension, as it is intended to be used in decision making processes by humans, based on their skills and knowledge. At the end, the humans are the ones that are making the decisions, or are the ones that are creating the decision making mechanisms. Mavrikios et al., (2007) have developed a concept of a Collaborative Manufacturing Environment (CME) advancing the capabilities of humans in areas of e.g. information sharing, knowledge management, and decision making.

The importance of the possibilities offered by ICT tools and principles is ever more acknowledged, not only in academia, but also in industry. The Strategic Multi-annual Roadmap, prepared by the Ad-Hoc Industrial Advisory Group for the Factories of the Future Public-Private Partnership (AIAG FoF PPP), lists ICT as one of the key enablers for improving manufacturing systems (FoF, 2010). The report describes the role of ICT at three levels; smart, virtual, and digital factories.

Smart factories involve process automation control, planning, simulation and optimisation technologies, robotics, and tools for sustainable manufacturing. *Virtual factories* focus on the value creation from global networked operations involving global supply chain management. *Digital factories* aim at a better understanding and the design of manufacturing systems for better product life cycle management involving simulation, modelling and management of knowledge.

2. DIGITAL, VIRTUAL, AND REAL

The division of manufacturing systems into digital, virtual, and real parts was first introduced in (Nylund et al., 2008) and has then been further developed in the context of a framework for Extended Digital Manufacturing Systems (EDMS) (Nylund and Andersson, 2011). It is aimed as a platform for collaboration between all manufacturing activities and related parties. The EDMS contains the digital information and knowledge of the real manufacturing system activities, as well as the computer aided tools for simulation, modelling, analysis, and change management of manufacturing systems.

2.1. MANUFACTURING ENTITIES

Internally, the manufacturing entities consist of digital, virtual, and real existences as their autonomy, and a communication part as the enabler of collaboration with other manufacturing entities. The internal structure of the manufacturing entities is presented in Figure 1.

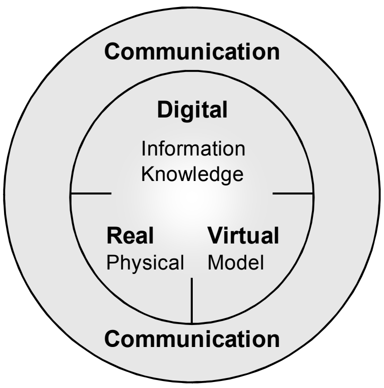

Figure 1 – Structure of a manufacturing entity (Nylund et al., 2008)

The real part represents what exists physically in a system while *the virtual part* is a presentation of the physical entity, usually as a computer model. *The digital part* holds the information and knowledge of the real and virtual parts to fully describe their characteristics and properties. *The communication* part is responsible for the collaboration activities between the entities.

The communication part connects the different manufacturing entities and enables viewing them on different structuring levels. Wiendahl et al., (2007) recognize five structuring levels in the context of changeability i.e. manufacturing networks, sites, segments, cells, and stations. Each level can be treated as a manufacturing entity, which consists of the entities on a lower level and their collaboration.

The connection of the structuring levels can be explained with, for example, Fractal Manufacturing Systems (FrMS). In FrMS, a fractal is an independently acting entity (on each of the structuring levels) that can be precisely described (Warnecke, 1993). For example, a manufacturing segment consists of manufacturing cells and their interaction. At the same time, it is a part of a manufacturing site interacting with other segments of the site.

2.2. MANUFACTURING SYSTEMS

In addition to describing the internal structure of a manufacturing system divided into digital, virtual, and real existences, the overall management of a manufacturing system can be explained with the same division. Figure 2 shows the basic principle of utilising the division by dividing a manufacturing system into its subsystems.

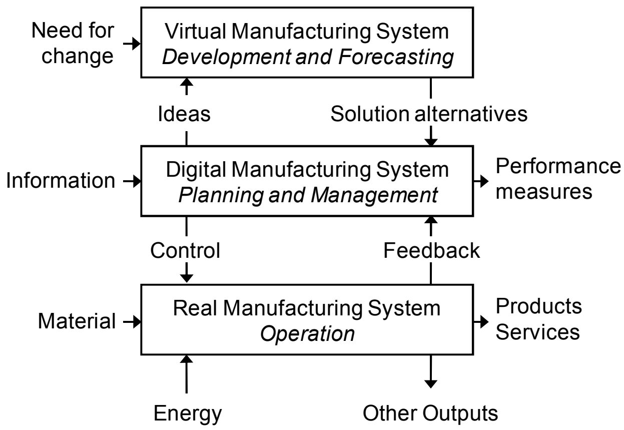

Figure 2 – Structure of a manufacturing system

The real manufacturing system is responsible for the physical operations, i.e. transforming material and components into finished products and related services. In addition to material, the operations consume energy and result in other outputs, such as removed and unused material, other forms of physical waste, and emissions. The behaviour of the real manufacturing system is controlled in the digital manufacturing system and the results of the activities are again analyzed the digital manufacturing system for planning and managing upcoming production activities.

The virtual manufacturing system can present the current manufacturing system or a proposed future version of the real manufacturing. In the case of the current system, it is usually used in forecasting e.g. simulating changes in production volume and mix. The development concerns the future of a system, where the effects of possible configuration changes or implementing new manufacturing resources can be experimented.

2.3. MANUFACTURING ACTIVITIES

In a manufacturing system, the autonomous manufacturing entities are acting and interacting with each other. The activities can be explained as services, loosely based on Service Oriented Architecture (SOA). SOA consists of self-describing components that support the composition of distributed applications (Papazoglou and Georgakopoulos, 2003) enabling the autonomous manufacturing entities to negotiate and share their information and knowledge. The basic conceptual model of the SOA architecture consists of service providers, service requesters, and service brokers (Barry, 2003). Applying the principles of SOA onto a manufacturing environment, the architecture can be explained as follows (Nylund and Andersson, 2010b):

- Products are service requesters when they are realized as orders send into a manufacturing system. They initiate service requests they require in order to be manufactured.
- Resources, such as machine tools, are service providers having the capabilities needed to provide the services that are requested.
- A service broker plays the role of managing and controlling the manufacturing activities. Its function is to find service providers for the requesters on the basis of criteria such as cost, quality, and time.

The actual service can occur in the real part as a physical transformation process, or in the virtual part as a simulation. The input information for the transformation process as well as the output information produced from the process exists in the digital part.

2.4. MANUFACTURING IMPROVEMENT

In (Nylund and Andersson, 2010a) improving a manufacturing system is discussed from the viewpoints of continuous, incremental, and radical improvements.

Continuous improvement focuses on keeping the current system running and eliminating the deteriorating of the system. From the digital point of view, it is mostly gathering predefined data from the daily manufacturing activities to measure and monitor the behaviour and variation of the system. By monitoring the values, beforehand defined actions can be taken, or in the lack of those, new plans for actions can be developed. From the virtual point of view, continuous improvement can be e.g. planning and scheduling using simulation solutions to fully utilize the potential of the system.

Incremental improvement focuses on the development of an existing system. It causes changes to the part or the function structure of the system. Typical issues include configuring the system to a new desired state, or implementing something new to meet the requirements of the desired state.

Radical improvement aims at something new that is more effective than the existing system. It questions the underlying assumptions on how the activities are currently conducted. From the digital and virtual points of view, it rather creates new incremental improvement activities, than requires digital or virtual activities itself.

One can argue that a radical improvement exists before an incremental improvement. It again creates changes for a continuous improvement. As the radical improvement happens rarely compared with the incremental improvement, most of the changes to continuous improvement occur without the radical improvement.

Any improvement activity aims at a better performing manufacturing system. The performing of manufacturing systems has to be able to be measured. Therefore, suitable performance metrics are required. Behn (2003) recognizes eight generally applicable purposes of measuring performance: to evaluate, control, budget, motivate, promote, celebrate, learn, and improve, where the improvement is the core purpose behind the other seven. Typical performance metrics for manufacturing improvement can be divided into manufacturing process monitoring, manufacturing flow efficiency, and competence of the company (Nylund et al., 2011b). Examples of performance metrics are discussed in Section 3.4.

3. RESEARCH ENVIRONMENT

The theoretical issues discussed are currently being examined in an academic research environment. The aim of the environment is to offer a research platform that can be utilised in:

- Designing, developing and testing current and future research topics.
- Prototyping possible solutions for industrial partners in ongoing research projects.
- Utilizing it as an educational environment for university students and company personnel to introduce the latest results in the area of intelligent manufacturing.

3.1. OVERVIEW OF THE ENVIRONMENT

The research environment consists of typical manufacturing resources and work pieces as physical entities. The resources of the research environment, offering different manufacturing capabilities, are (see Figure 3):

- Machine tools (a lathe and a machining centre) for machining operations.
- Robots for material handling and robotized machining operations.
- An automated storage for storing blank parts and finished work pieces.
- Laser devices for e.g. machining and surface treatment.
- A punch press, existing only virtually, for the punching of sheet metal parts. The real punch press is located at a factory of an industrial project partner company.

Figure 3 – Overview of the manufacturing resources of the research environment

The work pieces, which can be manufactured in the environment, are fairly simple cubical, cylindrical, and flat parts in shape. They have several parameterized features that can be varied within certain limits, e.g. dimensions (width, length, and depth), number of holes, internal corner radiuses, and sheet thickness. The main reasons for the parameterization are, firstly, that the number of different parts can be increased with the variation without having a large number of different types of parts. Secondly, the parameters can be set in a way where changing the parameters also requires capabilities of different kind i.e. different manufacturing resources are required. This gives more opportunities to compare alternative ways to manufacture the work pieces based on selected criteria, such as the cheapest or fastest way to manufacture a work piece.

3.2. VIEWPOINTS OF THE ENVIRONMENT

The research environment can be seen from the digital, virtual, and real viewpoints. Figure 4 shows the real and virtual views of the whole research environment. The environment can be viewed from three different structuring levels; the whole environment, machining and robot cells, and the individual machine tools and robots.

The real part of the environment exists in a heavy laboratory and is divided into two main areas, one including the robots and laser devices, and the second the machine tools and the automated storage. The real manufacturing entities on each structuring level have their corresponding computer models and simulation environments as their virtual parts.

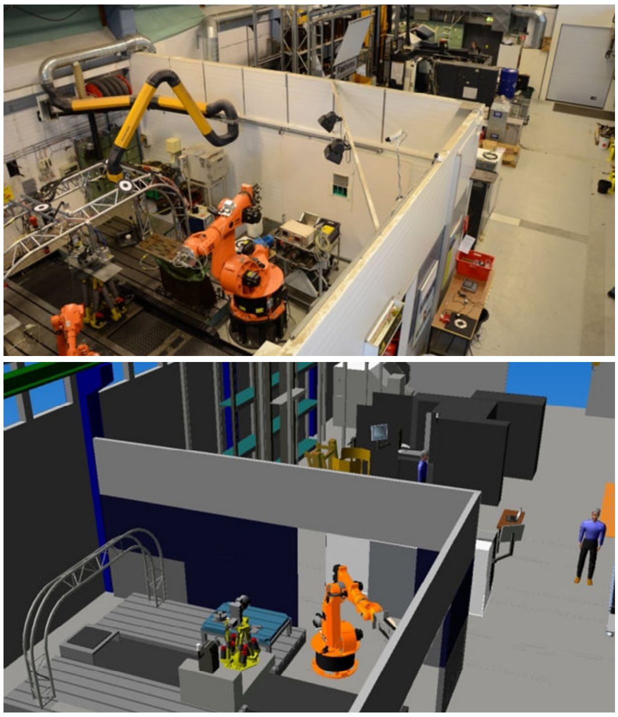

Figure 4 – Real and virtual views of the research environment

The information and knowledge of the environment is stored in local databases of the manufacturing entities as well as in a common Knowledge Base (KB) for the whole environment, those presenting the digital part of the environment. The actual connection is enabled by and executed via the KB, see (Lanz et al., 2008), as all communication activities use or update it. The KB is the base for the development activities of the research environment, presenting the role of a service broker. It is a system where the data of the environment can be stored and retrieved for and by different applications existing in the environment.

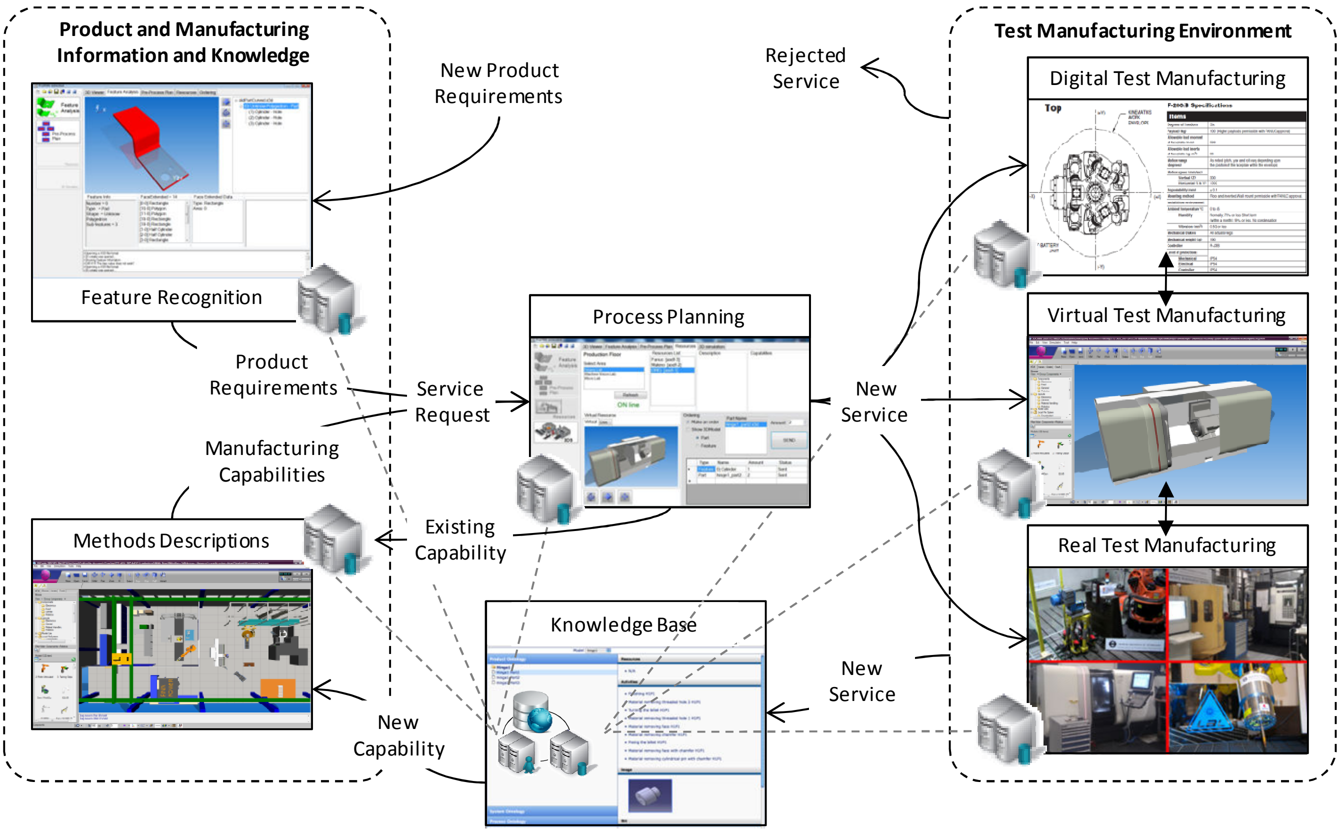

Figure 5 – An overall view of the manufacturing tests of the research environment (Nylund et al., 2011a)

3.2. MANUFACTURING CAPABILITIES

Figure 5 presents an overall view of the process starting from comparing new product requirements with manufacturing capabilities. The manufacturing methods of the resources form the manufacturing capabilities, which are formally presented and stored in the KB. Similarly, the product requirements are described formally and stored in the KB.

In the case of a new product, a CAD model is required. The model will be analyzed to recognize the features of the product. Each feature leads onto a service request, which is send to the process planning part of the environment. It includes the process plans of the environment that are known. It holds the information and knowledge of the manufacturing capabilities i.e. it can be seen as the digital memory of what has been manufactured within the environment. If a suitable service exists, i.e. this kind of feature has been manufactured before, the system will return a result that the feature can be manufactured. Otherwise, a new service request is created and the manufacturability of the feature can be tested.

3.3. TEST MANUFACTURING

The manufacturing tests can be divided into three categories; digital, virtual, and real test manufacturing. In principle the digital test manufacturing would be a favourable choice as it is basically comparing a set of parameters of a new service request to the formally described capabilities i.e. services that exist. The formal matching of product requirements and resource capabilities is currently under development, and at the moment, can cope with fairly simple scenarios.

The second choice would be a virtual test manufacturing i.e. typically modelling and simulation. It requires more time depending if existing simulation models can be used or new simulation models need to be constructed. In the case, where the existing simulation models cannot be used, new ones are required to be built. The creation of a new simulation model may be reconfiguring the existing virtual system, or implementing something new into the system. In these alternatives, the test manufacturing is still carried out with computers i.e. it does not interrupt the use of the real manufacturing resources.

The real test manufacturing requires the physical resources and the time used will reduce the time for daily operations to manufacture customer orders. The real test manufacturing will be the choice if the simulation models are not accurate enough to fully trust or understand their results. In some cases it is also reasonable to conduct additional tests with real manufacturing resources to reduce the risk of implementing fault processes.

The responsibility of selecting, whether digital or virtual test manufacturing would be enough, is to be determined by humans, based on their skills and knowledge of the matter in hand, and has to be evaluated separately for each time a decision needs to be made.

The result after the test manufacturing alternatives is either a rejected or an accepted new service. In a case of an accepted service, it is added into the KB as a new capability. The result of rejected service could happen if the product feature cannot be manufactured within the existing system, or even if it could be manufactured, it is e.g. too expensive, uses too much time or does not output desired quality. In these cases, the feedback goes back to the product development to consider it the feature can be redesigned.

3.4. PERFORMANCE METRICS

Several performance metrics are gathered from the manufacturing activities of the research environment. The metrics are used to monitor and maintain the operation of the environment as well as to measure the performance. The metrics are the same whether they are being collected from the simulation models or from the real system. Examples of metrics gathered from the research environment are:

- Delivery reliability, throughput and tact times
- Resource utilisation
- Process, changeover, and unit times and costs
- Work in progress and buffer sizes
- Production volume and material consumption
- Emissions, pollution, waste, and energy consumption
- Process quality assurance and stability monitoring

4. CONCLUSIONS AND FUTURE WORK

The digital, virtual, and real aspects of manufacturing systems were discussed in this paper. The main idea was to separate the digitally presented information and knowledge from the virtual models of manufacturing entities. The virtual part is the presentation of the real part i.e. a presentation of the same thing using ICT tools and principles, such as modelling and simulation, while the digital part is common for both of them, as it is used in the decision making in the overall management strategy of a manufacturing company.

The division into digital, virtual, and real aspects were used to explain the structures of individual manufacturing entities and systems as well as describing their role in manufacturing improvement and activities. These theoretical viewpoints were also explained in a context of an academic research environment, utilized in current research topics when applicable.

The research issues discussed in this paper are also utilized and further developed in several scientific research projects. Short descriptions of the topics of the selected research projects, related to the subject of this paper, are as follows:

Knowledge Intensive Product and Production Management from Concept to Re-cycle in Virtual Collaborative Environment (KIPPcolla). The project focuses on the development of better product-process knowledge exchange and knowledge intensive meaningful models. The main focus is on the digital part i.e. formalizing the ICT-related activities.

The CSM-Hotel project aims to create a concept to collect several small and medium enterprises (SMEs) under the same factory roof offering partially shared hardware and software resources and solutions for collaboration. This enables the companies to focus on their core competence and a new level of sustainability and can be reached. The research environment is used as a demonstration platform in the project.

Framework and toolset for developing, analyzing and controlling sustainable and competitive production networks (NICO). The project focuses on supporting Finnish companies in realizing competitive and sustainable products and production networks. Based on the identified requirements and best available practices of CSM, the research project will build higher level static analysis tools and simulation supported dynamic ICT tools for the design, implementation, measurement and development of CSM factories and networks.

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