

# Distributed Manufacturing (DM) - Smart Units and Collaborative Processes

Hermann Kuehnle

**Abstract**—Applications of the Hausdorff space and its mappings into tangent spaces are outlined, including their fractal dimensions and self-similarities. The paper details this theory set up and further describes virtualizations and atomization of manufacturing processes. It demonstrates novel concurrency principles that will guide manufacturing processes and resources configurations. Moreover, varying levels of details may be produced by up folding and breaking down of newly introduced generic models. This choice of layered generic models for units and systems aspects along specific aspects allows research work in parallel to other disciplines with the same focus on all levels of detail. More credit and easier access are granted to outside disciplines for enriching manufacturing grounds. Specific mappings and the layers give hints for chances for interdisciplinary outcomes and may highlight more details for interoperability standards, as already worked on the international level. The new rules are described, which require additional properties concerning all involved entities for defining distributed decision cycles, again on the base of self-similarity. All properties are further detailed and assigned to a maturity scale, eventually displaying the smartness maturity of a total shopfloor or a factory. The paper contributes to the intensive ongoing discussion in the field of intelligent distributed manufacturing and promotes solid concepts for implementations of Cyber Physical Systems and the Internet of Things into manufacturing industry, like industry 4.0, as discussed in German-speaking countries.

**Keywords**—Autonomous unit, Networkability, Smart manufacturing unit, Virtualization.

## I. INTRODUCTION

NEWLY available ICT devices offer so far unseen opportunities in manufacturing. Technologies for information processing and communication are about to embrace all important manufacturing areas. Real production increasingly melts with the digital production world [1]. With novel information technology, smarter equipment and networked units, many factories gradually turn into large computing units sending data across and outside companies [2]. Developments in ICT will totally reshape manufacturing as machines, and objects and equipment on the shopfloors will become smart and online, eventually resulting in smart distributed manufacturing [1]. Virtualizations and models of manufacturing units will interact exactly as interactions with the units [6]. Context aware equipment, autonomous orders, scalable machine capacity or networkable manufacturing units will be the terminology to get familiar with in manufacturing and in manufacturing management [7]. Such newly appearing

smart abilities with impact on network behavior, collaboration procedures and human resource development make decentralized distributed manufacturing a preferred model to produce [5]. In order to capture the full context, the accounting theory behind is identified as the mathematical topology. This topological framework enables to model the entire manufacturing network context coherently [10].

Numerous approaches for computerizing manufacturing units and processes propagate powerful and fascinating services, ready for implementation [3]. The appearance of novel devices, able to be positioned, to be tracked, and to be identified on one hand, also capable to communicate, to act, to negotiate and even to decide on the other is gaining influence on everything that concerns manufacturing [4]. As manufacturing increasingly supports the processes by means of virtualized smart resources, Distributed Manufacturing (DM) [5] irreversibly extends from automated factory floors onto manufacturing enterprises in total. Advances on the fields of embedded systems, and cyber physical systems [6] additionally accelerate this shift. Important developments are also telecommunication driven and discussed under different chapters, as Internet of things [7], Ubiquitous Computing [8], Smart Objects [9] or comparable terminology. Decentralization and atomization of processes, units and procedures and their virtualizations are in trend. Some principles that had been found for DM [10] now reappear for manufacturing in total, so most upcoming set ups can be mirrored to DM experiences and respective findings.

As various communities from different disciplines outside of manufacturing are intensively working on new services and novel devices, the most important developments are introduced in accordance with international, governmental or industrial institutions (e.g. NIST, 2011; Open China ICT, 2013; VDI/VDE, 2013). The proposed virtualizations are largely based on information models. In order to obtain closed and coherent descriptions of networks, topological spaces are introduced as a base for further discussions. The space construct, as outlined, reduces down to the essentials on one hand; on the other hand it is powerful enough to capture all relevant aspects of networked manufacturing. The possibility of smoothly attaching model worlds to the nodes of the space literally imposes interpretations of cyber physical production and smart objects. The resulting set of loosely coupled, autonomously acting manufacturing units are evidently subject to principles and modes of complex structures that are known from advanced mechatronic systems and DM set ups [10] already. In this context, procedures for controlling the behavior of units and the generalized principle of

H. Kuehnle is with the Mechanical Engineering Department, head of the chair of factory operation and manufacturing systems, Otto-von-Guericke-University Magdeburg, 39106 Magdeburg, Germany (fax: 0049(0)391/67-12404, e-mail: hermann.kuehnle@mb.uni-magdeburg.de).

encapsulation are outlined for generalization. All critical technologies for Smart DM are mature. Sensor and actuator networks, intelligent controls, planning models, plant performance optimization software, cyber-physical systems, security and other related devices are fully available on the market. Synthesized with model based engineering, systems integration technologies, open data analytics platforms, engineering information systems, and decision support methodologies at all levels, these devices are ready for use in DM.

The paper proposes a more comprehensive theory base for virtualizing manufacturing which helps to anticipate an emerging “smart age” of manufacturing. Practitioners should be provided with some trajectories on these rapid developments and expected impacts as inputs for their decisions and to verify their gut feelings for the next steps in organizing manufacturing network processes.

## II. SMART MANUFACTURING UNITS' PROPERTIES

As all smart units [11] manufacturing units, too, may be seen as specifications of the IoT and CPS. Manufacturing will increasingly appear as equipped by physical or/and digital objects, upgraded with sensing, processing, actuating and networking capabilities. Additional abilities, as environment-awareness or self-logging and self-reporting features further augment these objects and allow carrying many data about themselves as well as their activity domains. Moreover, smart units may make emerge network structures e.g. as results from their collaborative processes executed by manufacturing units striving for incentives (attractors). DM networks are being composed of self-optimising, self-orienting entities, managed as well as formed by defined rules. Network management establishes proper and genuine processes or initiates interactions, where units float within network configurations or collaborate and communicate on all levels of detail. Some configurations seem more favourable than others in some respect, so continuous monitoring has to evaluate for gradual and stepwise decisions or configuration alternatives; main issues are linking or detaching. In DM, business opportunities represent such governing “attractors”, giving inputs to drive, to operate and restructure manufacturing networks to build up and to optimize versatile collaborative process nets.

### A. Networkability

Smart units in DM have to exhibit strongest abilities to network. Networkability may be seen as both, the internal and external ability of units to collaborate, simultaneously considering all manufacturing process relevant aspects. Networkability is defined at the DM network level by giving out the rules for alignments of network configuration at all levels of detail of units and subnets. Networkability may be supported by implementing coordination mechanisms that evolve interrelations between units towards networked organizations.

Networkability of smart units is enhanced by sensing and actuating technologies, which capture the global and the local contexts of products, objects, other units, and communication

infrastructures, even IT models. In manufacturing, especially process and decision parameters are concerned with the aim of generating efficient processes, thus smart manufacturing units may even carry factory models, equipment geometries, process and task as well as interaction and decision models [12].

In order to harmonise the networks on all LoDs, the models, attached to the network entities, should demonstrate fold and unfold properties that originate e.g. from encapsulated generics.

For networks in manufacturing, aspect wise decompositions have already been successfully introduced as generic set up, distinguishing between aspects as information, organisation and processes similar to e.g. the specification of the CIM/OSA framework and consecutive standards [13]. Equivalent layer wise resource co-ordination schemes for networked manufacturing have also been successfully applied for enterprise units' networks elsewhere [14]. Smart DM proposes the layer wise decomposition to support networkability on all levels by keeping the aspects separate and tied together network wide at the same time, Fig. 1.

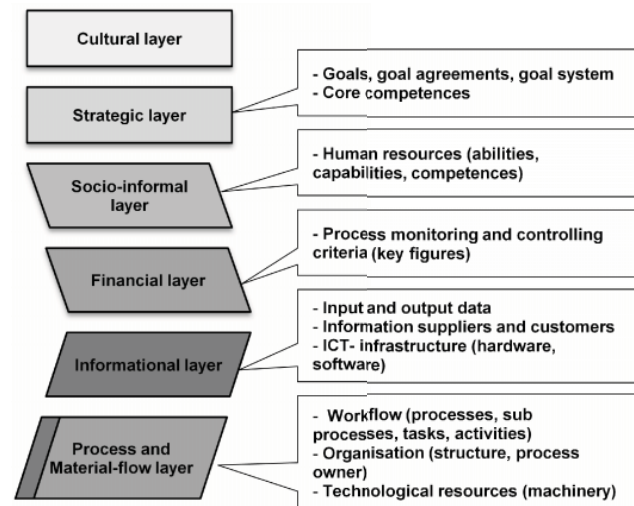


Fig. 1 Process and manufacturing unit modelled by 6 layer descriptions

1. The culture layer envisions the network as a social system and captures the value and thinking pattern within the network. Consistent values are prerequisite for the networks' success.
2. The strategy layer describes the way, the network deals with the market and the resources. To quantify strategies, networks use objective systems, describing the actions of a network towards markets, economical pressure, and technological changes.
3. The social-informal layer models the HR and organisation contexts of the network. It includes all kinds of social and informal factors that determine and influence relationships within the network. Given that the network relies on autonomous units, teaming and communication skills' elements prove to be important.

4. The financial layer deals with the evaluation of performance and the allocation of value addition across the network.
5. The information layer primarily addresses the design and handling of the flow of information. The major challenge is, to back up interconnections and re-configurability of devices or IT infrastructure. Smart units are equipped with computing units. Control systems are emulated using different networkable operating systems.

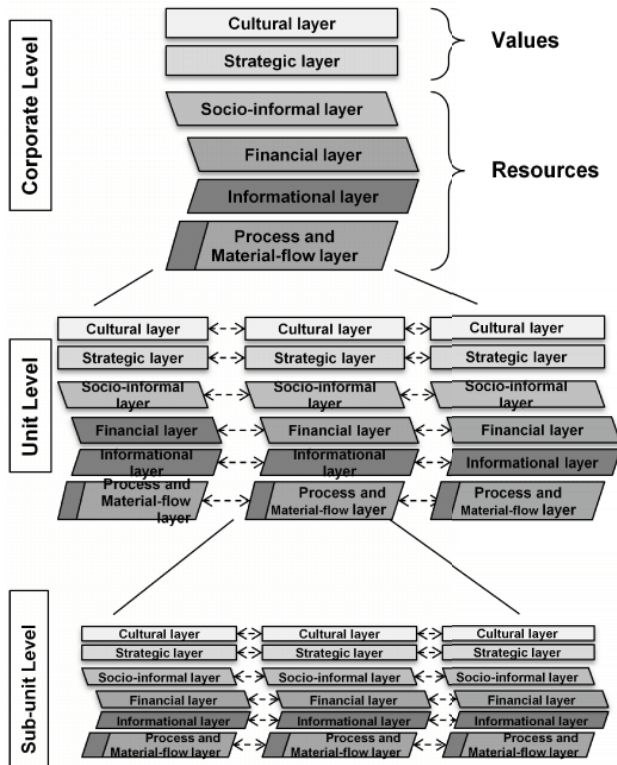


Fig. 2 (a) Generic Units' Layer model applied to Levels of Detail (Self-Similarity)

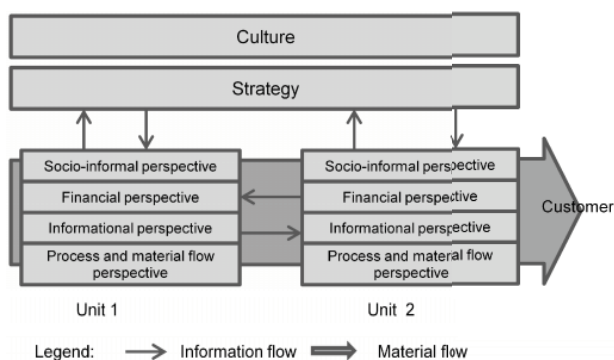


Fig. 2 (b) Networking (Layerwise Harmonization).

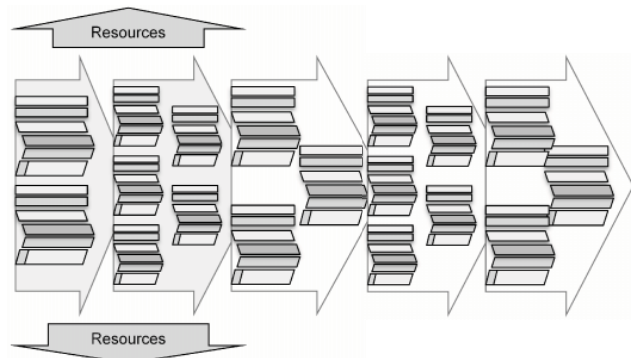


Fig. 3 Basic Collaborative Process composed of Layer described Units

6. The layer of process and material flow addresses the technical and physical side of the transformation steps. Technical function descriptions as well as logistics and materials handling are covered. Dependent on the case and the level of detail to be addressed, fold and unfold properties are embedded to meet the corresponding levels of detail for communication between different entities.

The layers also support the syntheses of network frameworks with specific priorities of aspects e.g. human centred team concepts or purely ICT driven units by layer-wise descriptions of interconnections of units, maintaining the complete aspect views throughout the entire networks on all levels of detail (Fig. 2).

In DM networkability of units has to promote the configuration of inter-unit collaborative processes on all layers. This includes the decision abilities, providing all procedures involved in governing and executing the necessary activities for (re)designing and setting up new or restructured processes. Processes in DM may be defined as an inter-related set of functions, ordered by precedence relationships, triggered by event(s) and producing observable results [15].

Networkable decisions to be taken result in processes' configurations used as:

- descriptive mapping illustrating performed or running processes for analysing and extracting process parameters;
- prescriptive mapping, supplying anticipated process options for further evaluation and networks evolution and
- prospective instrument, displaying eventual configurations for evaluation which configurations should be preferred or avoided.

Activities and functions of the units may easily be structured according to the levels of detail, well differentiated according to the relevant network aspects. These generic models may as well be considered for process descriptions as they include the key constituents. They may be implemented according to the units' levels of detail and the units are assumed to organise tasks and activities respectively (Fig. 3). Orders, process segments and tasks may e.g. be executed via software agents.

Based on the basic concept for the model the thematic approaches, i.e. product and resource, represented by agents,



may be composed more detailed as a configured process network as results of agents interactions.

The introduced aspect layers of network ability do not only allow describing the units and prepare setups for interrelations. The layers also allow narrowing down a number of properties and smart manufacturing units are expected to exhibit in DM. These properties will not have to be newly engineered; it suffices to select and specify from the already existing devices.

#### *B. Acceptance of Existing Boundaries and Network Participation*

Each smart manufacturing unit has to carry its digital presence, uniquely identified in the digital world, which includes ID and network interface address or other application-specific high level naming. Existing boundaries of the DM network must be accepted. This also affects the hierarchies of the (traditional) manufacturing systems in ERP, MES and shopfloor terms with clear responsibilities for factory equipment such as machines or factory sections. Smart manufacturing units should always retain its original functionalities and appearances, and maintenance should extend their physical usages so it is mandatory to decouple the augmented features from the original unit features. Smart units must support its original functions and properties, even if the augmented electronic cyber part is out of order.

Moreover, the requiring interactions with smart units should be identical to interactions with the original object. Mental models, cast into emulation that keep the instrumentation implicit (without additional interactions), will make humans commonly experience that they are dealing with the physical real objects rather than their digital abstract objects.

#### *C. Context Awareness*

A smart unit is augmented with various technologies, thus it is expected that a smart unit is able of knowing its operational and situational states and should be able to describe itself. This awareness might be also be provided by a secondary infrastructure e.g. cloud.

Awareness is generally defined as the ability to provide services with full awareness of the current execution environment. As any information that can be used to characterize the situation of entities (i.e. a person, place or object) that are considered relevant to the interaction, including the user and the applications themselves.

Aware units offer functionalities for gathering context data and adapting behaviour accordingly, aware systems, as cyber-physical systems, are by nature concurrent, as establishing and running processes are intrinsically concurrent and the coupling with computing shows concurrent composition of computing processes with the physical ones by definition.

Using sensors and actuators, once recognised gaps and deviations may be stated and reconfigurations and adaptations may be initiated for determining current states of the models and vice versa, displayed effects may induce actions in the real world. Manufacturing information, which has been handed out as specs, work sheets, drawings, or schedule information, are

now instantly and very precisely available enabling prompt identification, processing and communication of between actual and planned states and parameters.

To represent the current network states in a model system as well as to bring in modifications (e.g. for optimisation) from the model world into the real world, the different “network worlds” may be stored as models and gradually harmonized, so each action in the real manufacturing world may have an effect on the models and vice versa result in reactions towards the environment. Adequate set ups may be characterised as:

- (1) A set of models that allows us to properly represent the context information at conceptual level. These models are capable to describe information related to objective fulfilment, position within the environment, location aspects and behaviour policies, as well as to the users that can interact with the system.
- (2) Strategies and the decision procedures to allow the units to take adequate measures or to anticipate failures and to adapt the models according to new context data [16].

The set ups must as well depict a number of alternatives of possible states or configurations that might be chosen for further optimisation. However, history and time might keep from taking decisions in these directions and may therefore configurations be kept as future options. This notion of model thresholds is also called Dual Reality [17], (possibly extended to multiple realities)); the “gradual iterative” decision mechanisms behind are outlined in [12].

#### *D. Heterogeneity*

Heterogeneity of units is referred to as the properties of units being composed of diverse elements and using dissimilar constituents. In DM, heterogeneous manufacturing units and their constituents configure a networked and have to closely collaborate. Overcoming heterogeneity is a central issue in DM, as, due to the variety of devices and units involved, DM is intrinsically heterogeneous. The units or their constituents are to be connected and to configure networks comprising different types of computing units, potentially with vastly differing memory sizes, processing power, or basic software architecture. In DM, heterogeneity may therefore be assumed omnipresent, it occurs on all levels and for a number of reasons. On the informational side, heterogeneity may additionally come with different hardware platforms, operating systems, or programming languages. On the conceptual level, heterogeneity originates from different understandings and modelling principles for the same real-world phenomena.

Basically, two ways of coping with heterogeneous systems can be differentiated:

1. Establishing a comprehensive unified theory and
2. Providing abstract data models and semantics.

In smart DM both directions are recognized. Inherent heterogeneity- and integration issues of different components as well as all challenges around are treated with novel unifying network and control theory. The generic layer aspects of the introduced model definitely allow separating heterogeneous connectivity and collaboration issues as well as

keep their break downs and fold ups. Therefore enabling interactions between sets of heterogeneous ICT devices of different brands and marks, i.e. interoperability, is condition sine qua non in any DM scenario.

Moreover, heterogeneous networks require permanent revision of network components with emphasis on real-time operations requirements, so communication and sensing, actuating and processing in meshed control loops are supported

#### *E. Interoperability*

The property of diverse systems and subsystems to work together (inter-operate) is referred to as interoperability. Interoperability is defined, as soon as operable units are available. Operability itself refers to the ability to safely and reliably run a system, in line with general and unit specific requirements. IEEE [18] defines interoperability as the ability of two or more systems or components to exchange information and to use the information that has been exchanged. Interoperability can be understood as the capability of ICT systems as well as all supporting processes to exchange data as well as to allow sharing of information and knowledge.

Issues in collaboration and co-operation of units appear in larger contexts as communication between people, communication between people and ICTs and also between different ICTs. Consequently several levels of interoperability are differentiated. Furthermore, IEC TC 65/290/DC identifies levels of compatibility depending on the quality of communication and application features in a cumulative scale. Especially the term of Interchangeability is used as intermediate level of communication and expresses an ultimate interoperation. TCP/IP includes mechanisms that address automatically; the most important implementations are SLP, zero config, universal plug and play and UPnP. Combinations of services and processes, as desired in DM, are e.g. supported by service oriented architecture (SOA). Functions are not addressed directly; instead services are requested via defined interfaces. The service program acts as an intermittent between the client and the provider. SOA is therefore an important vehicle for pay services and a significant step towards new concepts of smart DM for addressing services via networks according to usage, as e.g. offered by cloud providers. The major achievement of SOA is the principle of encapsulation for implementing functionalities on its generic level supporting fold unfold principles by hiding or forgetting functionalities in certain situations. Encapsulation also supports mappings between functionalities on different levels of detail of the equipment and various stages of granularity.

#### *F. Autonomy*

Units demonstrate autonomy or are called autonomous, if these units are able to perform their actions without the intervention of other entities. Autonomy includes the ability to interact or to self-organise in response to external stimuli, establishing a positive self-fed loop with the environment.

Innovations and developments have rapidly contributed to higher intelligence of a number of manufacturing units allowing self-organisation, self control and eventually full autonomy of factory objects and units (Cloud). Autonomous units may now do their communication independently and may decide how to handle interactions with the outside world, by use of de-centralised decision making and by the formations of autonomous hub organisations with own rules and procedures within a collaborative process or supply network. For differentiation of actions and decision mechanisms in context aware manufacturing equipment, a differentiation of context dimensions may be introduced [19]:

- External (physical) refers to context that or captured by units' interactions or can be measured by hardware sensors, i.e. location, movement, alignment parameters, strategic input
- Internal (logical) is unit specific, i.e., goals, tasks, objectives fulfilments, KPIs, improvement effects, operations or processes.

Dependent on captured and monitored data, events or stimuli, a manufacturing object may have to become active. Most important are models for decision procedures, so the manufacturing objects can adequately respond to monitoring results, if actions are required. Models to support units on the decision making also regard possible strategies to activate, guaranteeing adequate alignment and the preconditions and cases in which these strategies could be activated. The objective in the model is to maximise the performance obtained through the strategies activation, considering that an active strategy positively or negatively influences the KPIs defined to measure an objective.

Smart units may have capabilities to take certain actions as simple as switching from state to state or as complex as adapting the behaviour by other decision-making, action plans for self-healing, self organising and self sustaining. Depending of the smartness of the unit, the degree of autonomy may vary.

The starting point for a definition of a unit's autonomy is the ability of units to independently define and negotiate own objectives and pursuing strategies to achieve or to approach objectives. Within DM processes, autonomies are always restricted by the mode how other network units activate their strategies and how they define their objectives. Alignment of strategies and the harmonization of objectives include decisions concerning partners' selection, contract agreements, objectives' re-definition and performances as well. The network units have to keep own objectives and network objectives aligned with other units objectives in the network or check modified structures for collaboration by adapting or renegotiating links, restructuring network solutions and confirm or revise missions. Reciprocally, any misalignments will result in possible conflicts between the implemented strategies and the defined objectives, jeopardizing the benefits of collaboration or even breaking up processes. Misalignments and overstretching of the resource base certainly reduce or eliminate a unit's autonomy.

Standard Objective Bundle and negotiation of objectives is outlined in [10]. A respective commercialised method for

assisting in designing and identifying the goals has come up as Goal Directed Task Analysis (GDTA) process, Fig. 4. Actionable sub-goals ultimately achieve the original goal. For each sub-goal it must be considered how the operator will attain Level 1 projection, Level 2 comprehension, and ultimately Level 3 perception. Once, the business goals of a unit are clearly understood the configuration can be designed.

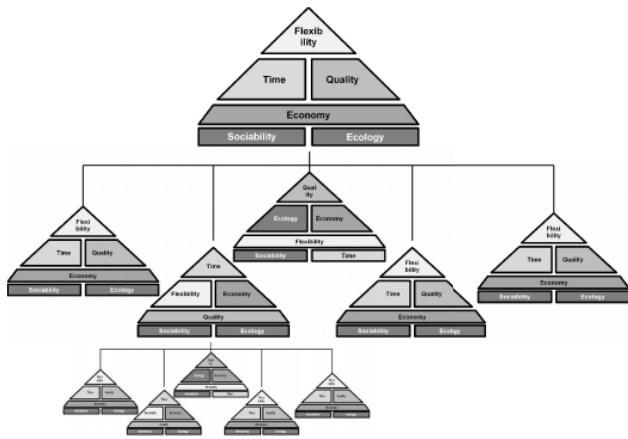


Fig. 4 (a) Break - down of network standard objective systems according to self-similarity principles [12]

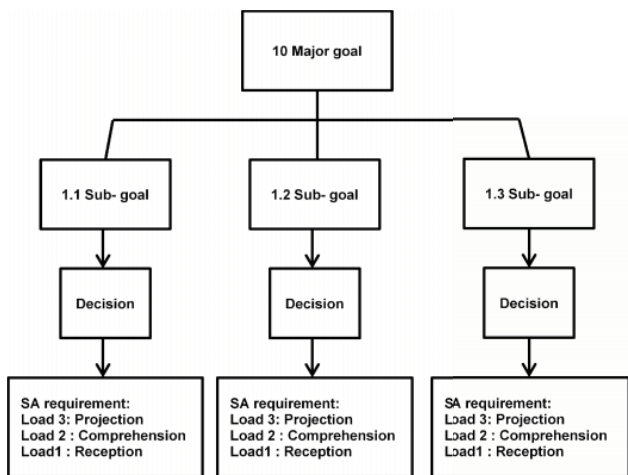


Fig. 4 (b) Break - down of network standard objective systems according to self-similarity principles [12], implemented as GTDA software design [20]

### G. Modularity

Units are considered modular, if they can be decomposed into components that may be interchanged and matched in various configurations. The respective components are able to interact, to connect, to exchange resources, using standardized interfaces. Different from monolithic systems, modular units are loosely coupled. Modularization entails the ability of processes, information systems and products to be packaged as reusable modules that can be (re-) combined with other modules, collectively making up new, value-adding artefacts. Modularity relates to the degree of dependency of elements of the module and is realized by allowing loose coupling between

modules, implying that modules should have as little interdependencies as possible. In this manner, modular designed objects behave like autonomous network constituents, which can be networked in a relatively straightforward way. Standardization is the coordination mechanism of preference allowing modular networked objects to be synthesized in a standard manner, decreasing the need for mutual agreements on interoperability. As modularity in manufacturing is not a new concept, there are already examples of modules in DM systems, especially in the areas of control systems, equipment design, and human resource development and in enterprise management.

The intrinsically heterogeneous nature of modular systems enables to cope with various technologies and tools. In manufacturing successful use of modularity is mostly based on the ability to align process steps involving different units in order to form viable and efficient value chains by transmitting and exchanging data in a seamless way. Abilities to combine modules, abilities to understand systems of systems and its components and variably combining these, are crucial.

Naturally associated with modularity is the property of compositionality, which means that higher level systems' properties can be derived from the local properties of individual components. Compositionality is frequently impacted by strong interdependencies of software and systems adequately designed with embedded higher level properties.

Major challenges for modularity are especially the alignments of human resource practices and information systems, so fragmented operations can be adequately supported by human capabilities. More intelligent units, e.g. smart objects, will enclose control and decision processing. It is decisive, in which way the units or activities are interconnected. Modularity also implies that, aside local feedback and local decision-making, capabilities are offered for prioritizing task allocation and capabilities are available for the execution of partial process chains.

### H. Scalability

The capability to extend/reduce resources in a way, that no major changes in structure or application of technology are necessary, is generally referred to as scalability. Due to stronger links between cyber objects and real manufacturing units, the term of scalability evidently becomes highly relevant for DM and manufacturing networks. Of course, a main concern is the capacities' scalability, i.e. the facility to increase or decrease necessary resources to efficiently accommodate broadly varying capacity loads. For example, cloud manufacturing gives the cloud consumers options to quickly search for, request and fully utilize resources procedures, e.g. search for idle and/or redundant machines and hard tools also in other organizations, in order to scale up manufacturing capacity.

Scalability can be seen as one important requirement to realize self organization in DM as it enables adapting processes rapidly in highly dynamic environments. Moreover, in DM, such adaptation processes are gaining importance in plug & work applications. Scalability may refer to the



commodity background as discussed in the remote manufacturing cloud, e.g. more machines of the same type in different sites or different companies to fulfil large order quantities in shorter time. Another field of scalability discussions is the area of control and computing power in the area of cloud computing.

### III. CONCURRENCY MODES AND MECHANISMS - MODELS OF MANUFACTURING

Whenever we talk about interacting, negotiating and communicating objects, we always talk about respective models of these objects performing such activities. Also planning, decision and execution in manufacturing do obviously not regard the units themselves but certain models and attributes of these units that configure and are put into relations. Each step may make use of a number of models interacting, raising the question of how their dependencies and simultaneous actions influence choices, highlight attributes or require certain levels of detail of these models to be involved. The manufacturing network units' interaction structure must be envisioned as an interrelations' structure of specific models, representing these units. Envisioned like this, manufacturing does not just consist of simple units but of objects that encapsulate rich model structures, able to unfold numerous attributes and properties into the attached realm of models.

Manufacturing networks may then be interpreted as specific Hausdorff spaces. The topological nature of Hausdorff spaces allows identifying network units (nodes) and to attach tangent spaces to each one [21]. The set-up is rich enough to capture a vast majority of configurations and decision situations occurring in manufacturing networks. This is accomplished by "attaching" tangent spaces carrying adequate models, attributes, relations and aspects assigned to the manufacturing networks' nodes (Fig. 5). Moreover, these virtualisations of manufacturing objects, also called mappings, capture e.g. encapsulations of behaviour, fold and unfold properties, on-off modes of self-organisation. Configurations may be mapped and monitored as well by models, indicators and attributes, and the views are expressed by composite attached models, the reason why all mappings are assumed to be homeomorphous.

#### Production Networks as Hausdorff Space with Tangent Spaces

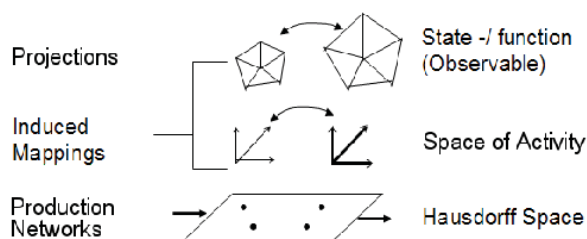


Fig. 5 Production Networks' units with attached tangent spaces (models) as mappings of Hausdorff Space nodes according to [22]

In practical terms, the homomorphism postulate stands for

compatibility of models of different units. Models of tasks of different units can form a process flow model only and models of machines of different units compose a useful layout only, if the respective units' models are compatible. To be able to do this easily, all involved virtualisations of the units will have to be standardised in some way, so a collection of units represented by attached models is instantly able to link, to interact and to execute important procedures e.g. for manufacturing planning, structuring, operating, linking, improving and deciding.

To answer the question about which models are to be attached for manufacturing applications, which properties and attributes ought to be mapped, the chapters of manufacturing systems planning and control history may be recalled. With the sophistication of manufacturing, important abstractions and experiences have been consolidated into a collection of generally recognised models, instruments and tools. With the introduction of computers in manufacturing, many of these models and instruments (or derivatives thereof) have been successfully incorporated in standard software e.g. ERP, Cave, DSS or facilities' planners. Manufacturing management generally makes intensive use of these models and model systems for specific problem solving, routine decisions and planning support, for instance for shopfloor planning, adequate models are flow charts, Sankey graphs, DMU/VR based on geometry data of buildings and machines.

As one trajectory for future manufacturing it may be kept in mind, that manufacturing units may be imagined as carrying all the models discussed above ready for application to link, to compose, to negotiate and to decide (processed by own computing power or remote). Manufacturing then appears as a set of loosely coupled autonomous smart units, spontaneously forming networks and executing processes; concurrent and evolving planning; negotiating decisions, all by interrelating models. This appearing set up seems to be quite different from what we are accustomed to when describing manufacturing and manufacturing management. Therefore it may be considered worthwhile to take a closer look at this emerging world of smart manufacturing units and the rules of the game there and to search for characteristics and principles.

On a smaller scale, many of the phenomena stated have already been encountered with configurations of DM [5]. Seeing all the similarities, the attempt to generalise and widen up important principles that have been identified for loosely coupled manufacturing systems, to the manufacturing networks' level, appears most promising. For start, a list of properties for smart units in manufacturing may be given that support compounding manufacturing processes of networked elements. Most of the capabilities, which smart objects for general use include already, are suitable for manufacturing process set ups, therefore their adaptation is less a question of requirements fulfilment, and it seems to be more a specification matter.

Recognizing these potentials is surely not exaggerated to postulate the necessity of a complete re-thinking of manufacturing and a thorough revision of every well established and habitually used, so far proven and

uncontested, manufacturing setup. It's not only the fact that all solutions have been set up without employing such options and technical possibilities, it is no longer possible to establish factory centred solutions on the base of pure systems thinking, widely ignoring the network nature of manufacturing. Most prominent examples are deeply rooted for example the term of process and supply chain in manufacturing; in reality we work on the base of process and transformation stage networks, which expose process chains ex post as planning and decision results.

#### A. Behavior

Behaviour is the range of actions made by systems, or abstract units, in interaction with other units and the environment. A unit shows its state in indicators (variables, data) and exposes its behaviour through methods (functions) that react to certain events. Process parameters present the behaviour of a unit and its interactions with other objects. Monitoring tools enable the users to specify and to process-level events such as inter process communication, as long as these events are at the correct level of abstraction of the network units, as successfully applied in DM [5]. As a representation of the units' behaviour, Spaces of Activity (SoA) may be described by the units' objectives, the resources and constraints. In consequence, the SoA volume may be identified as the unit's decision space i.e. admitted zone for the units' state (Fig. 6). The unit's behaviour, e.g. expressed by corresponding indicators, gives input for decisions on maintaining the unit's self-organization mode or reducing autonomy and calling for external interference. In cases of a unit's inability to cope with the objectives or the changes in the environment, network "order parameters" may gain influence on the units' activities ((self) reproduction, (self) destruction, (self) structuring).

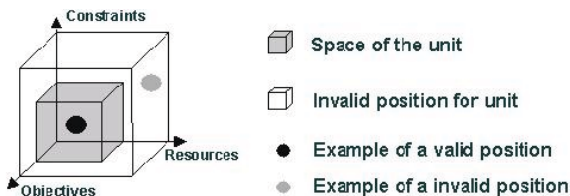


Fig. 6 Space of Activity (SoA) as mapping of network node for monitoring the Behaviour of the unit by relevant indicators and observable

This "biologically" inspired manufacturing approach addresses challenges in complex (unpredictable) manufacturing environments tackling aspects of self-organization, learning, evolution and adaptation [23]. They easily adapt to unforeseen changes in the manufacturing environment, and achieve global behaviour through interaction among units [24]. Applied for manufacturing network decisions, such behaviour thinking supports levelled manufacturing network adaptation procedures.

#### B. Parallelism

An optimum base for collaborating using least resources

and time is to do substantial steps towards parallelism of all actions and operations. Parallelism aims at reducing execution time or improving throughput. Adding parallelism to an event driven view requires reasoning about all possible chains of transitions to determine events that might interfere with others.

Parallelism for mobile applications uses operation time and requires sophisticated algorithms since it is not sufficient to run just a few services in parallel. Mobile systems are power constrained but improved wireless connectivity enables shifting computations to servers or the cloud. Leading experts state that, generally, parallel systems can be expected supporting task parallelism and data parallelism, both essential for decentralised and DM applications. Eventually each node of a task can have multiple implementations that target different architecture [8]. For manufacturing applications this allows taking full advantage of the task parallelism on one hand and running independent operations in parallel on the other. Parallelism will revise process planning, for example, by building sequences from independent sub-sequences. For parallelism of operations in manufacturing, industrial networks will strongly rely upon dynamic forms of communication and coordination that handle non-predictable situations by self-adaptiveness and self organization.

#### C. Iteration

Developing configuration options and decide about favourable configurations is a highly iterative process and not a straight-line journey. Loops back are possible, as factory and network capabilities identified and may not fit or others may give rise to potential new business opportunities. The 'Iteration' mode emphasises the fact that there is an inherent, evolving nature to structuring. Iteration results in changes that must propagate through the structure's stages, requiring continuous process rework. Within simple settings of collocated operations, the challenge of managing can still be achieved by conventional planning systems and respective intra-organisational decision mechanisms. For networks, management becomes much more complicated, as the involved units and their roles are not stable, but evolve dynamically. However precisely these properties enormously increase a companies' adaptabilities and strongly amplify differentiations and uniqueness. This means continuous restructurings and adaptations for manufacturing networks as well. For the decisions on structuring, re-linking, or breaking up connections in manufacturing networks, iterative procedures develop both system structure models and map behaviours onto structures vice versa, ensure the manufacturing networks robustness, their stability against uncertainties, operator mistakes, or imperfections in physical and/or cyber components. Since integration into processes must be orchestrated in order to achieve suitable performance behaviours, it is necessary to ensure the expected alignment with respect to the fit degrees, similar KPI or (estimated values of) key alignment indicators (KAI) [15].

#### D. Encapsulation

In general, encapsulation is the inclusion of one thing



within another thing so the included thing is not apparent. In DM, encapsulation is concerned with the possible encapsulations of abstractions of units (e.g. models or task descriptions) and transformations (e.g. processes) [5]. The Encapsulation mode enables to build networks and processes by combining elements for creating new processes and units or for atomising units to obtain elements. Self-similarity and compositionality of a unit or a process is a direct consequence of unit- or task encapsulation and provides the basis for constructing networks from components [25]. The models of a unit are accessible through interactions at the interfaces supported by the models. The model element may be seen as based on connectors (links) to construct and compose units. In the tangent space projection, there are two kinds of elements: (i) unit models, and (ii) connectors.

The units are loosely coupled and their control is originated and encapsulated by connectors, which is used to define and coordinate the control for a set of components (element or composite). Indeed, the hierarchical nature of the connectors means that composite units are self-similar to their sub-components; this property also provides the basis for hierarchical composition. Each unit model may additionally encapsulate more models and methods.

In a composite, encapsulations in the sub- units are preserved. As a result, encapsulation is propagated in compositions of newly constructed components (units are self-similar) and is also closely related to components' reuse.

Encapsulated models of units and connectors, may arbitrarily be compressed/broken down resp. fold/unfold (Fig. 7). For instance a critical behaviour of a unit on a lower level may have to be compensated on a more aggregated network level or even at the configuration level of the total manufacturing network.

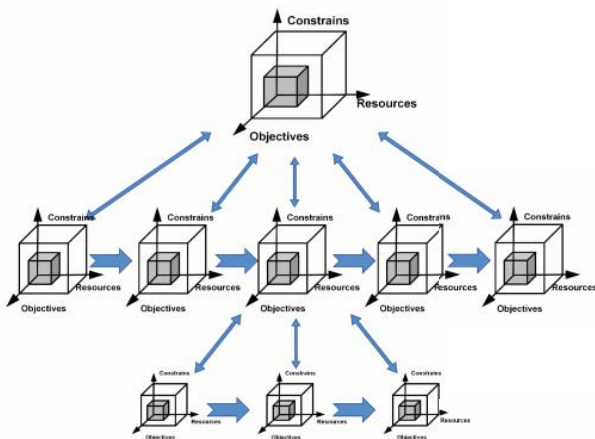


Fig. 7 Breakdown (unfolding) of encapsulated behavior models including criticality spaces into desired Levels of Detail

Arising criticalities are to be negotiated and harmonized with other units' objectives and resources. A unit's behaviour may generally result in decisions on maintaining the self-organization mode, reducing or removing the autonomy and calling for network interference along the subsequent decision

cycle.

#### Strategy and Objectives:

The network gets vision, mission and network draft that are later detailed to design and operation. The network strategy has to support the idea that in order to truly align the structure with business requirements, units must be free to negotiate and to choose the solutions that best meet their unique needs.

#### Monitoring and Analysis:

This stage tracks the execution of the manufacturing processes. It executes by detecting/ sensing the current state of the business and operational manufacturing environment, by monitoring the manufacturing-related business processes for determining if the manufacturing units' behaviours are acceptable (e.g., concerning economic performance), for capturing (unexpected) events and continuously informing on the current situation (e.g., desired, undesired and unexpected events). Activities that constantly update the units' potentials, capabilities or availabilities or that check the network for underperforming units and that notify the network in cases of outages or other alarms, recognized by units' criticalities. Structures, mechanisms and outputs are studied, compared and rated. These analyses may be driven down to sub or sub-sub levels where resource configurations and their contributions to the objectives as well as the SoAs structures (incl. the criticality settings) are broken down. In cases of less severe criticalities, improvements or objectives' alignments are initiated. Severe criticalities will provoke networks' adaptations or reconfigurations.

#### Network Design:

The network is be configured to meet customer requirements best. Partners, units and other actors are identified and linked to a network structure. Processes have to be linked and assigned to responsibilities.

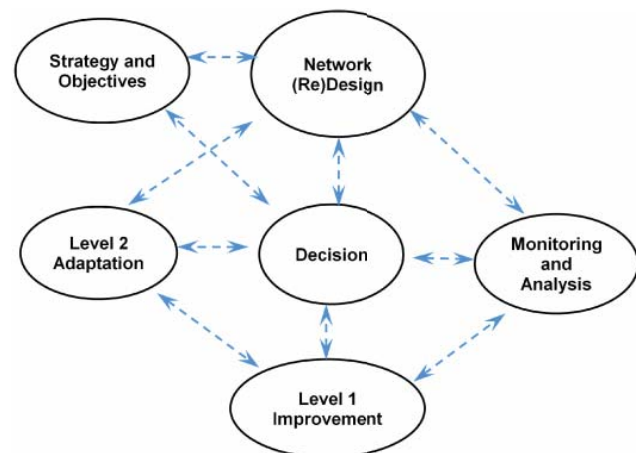


Fig. 8 Revolving decision cycle procedure of leveled interventions in Manufacturing for gradual continuous configuration

The strategy elements may be broken down to the decisive factors and the respective indicators that cover all key areas of the networks. They may result in relations of sub objectives

and/or aggregated objectives' systems.

#### Decision:

The decision phase marks the point where the necessary initiatives are taken in order to support the networks evolution into the intended direction. All decisions of importance may be taken, revised, improved or repeatedly cancelled within this cyclic procedure (Fig. 8) i.e. previous program strategy, network configuration, make/buy decision, site decision, process/technology/equipment decisions, etc. are revisited regularly. History and time (complexity attributes) might hinder to execute the resulting decisions immediately. Structures might exist that cannot be instantly eliminated or the building of new competencies will take some time. For the modeling of the network it is therefore recommended to maintain other models (structure simulator) beside the model of the given actual network. These models should provide for "what if" evaluations and simulated comparisons of indicators that make visible, to what extent the actual configuration has "suboptimal" effects on the results.

Fig. 9 illustrates the self-similarity of composite components in a decision network involving the decision cycle as described. Most importantly, every composite component is similar to all sub-components. This means that composition is done in a hierarchical manner. Furthermore, each composition preserves encapsulation. The topological nature ensures that the hierarchical structure of the process is enforced and the encapsulation enforces additional rules to ensure the overall process optimum. A unit component encapsulates all necessary models and procedures. A composite component also encapsulates computation and control [25]. For decentralized decision making based on network business models special logics, algorithms and methods for integration and management seem to be necessary. This concerns the matching of partners as well as the temporary collocation of operations in manufacturing networks. On this basis, all units' behaviour as well as all interrelations may be optimised and planning procedures and logic for the meshed control of configurations, containing processes and resources in networked manufacturing structures, may be established.

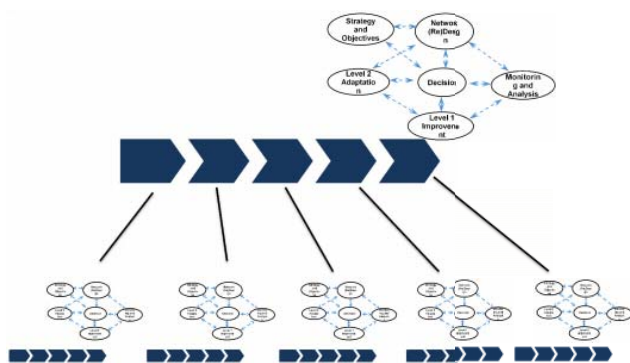


Fig. 9 Meshed decision cycles including encapsulated models and instruments to negotiate and decide on manufacturing networks' process fulfillment on several levels of detail according to DM/properties

#### E. Emergence

Emergence focuses on the arising of new patterns, structures and characteristics of networks that are neither really predictable nor fully deductible from antecedent states, events or conditions. DM configurations are ideally envisioned as emergent. Generally, emerging set-ups are characterised as dynamical, meaning they arise over time, as coherent, meaning show somehow enduring integration and occasionally as ostensive, meaning they appear during a set up evolves.

In the smart world as outlined, manufacturing processes may therefore be seen as emergent items as well, corresponding to the term emergence precisely in this sense. Complexity science has means to express links and dynamics of interconnectivity, (or what in complexity discourse is termed "emergence"; arising of unforeseen new structures with unexpected new properties [26]. In Fig. 7 the process chain emerges as a result of the interactions between units. There is no ultimate configuration solution beyond continuous adaptation and restructuring. To say that process chains emerge, however, does not mean to abandon overall planning. Rather than deriving outcomes by rigid adherence to preconceived strategies, the key for ensuring good solutions is to focus on creating effective rules for interactions. These rules ensure alignments among participants that increase the likelihood of favourable emergent network configuration leading to the objectives fulfillments aimed at.

#### IV. CONCLUSIONS AND OUTLOOK

What definitely follows for industrial practice is that non-hierarchical views of manufacturing will fully establish. Iterative concepts of event-driven parallel distributed evolving logics for planning and control will outdate centralist, sequential, rhythmic and time slicing procedures. Manufacturing will introduce and apply new types of methods and tools, supporting linkage and reconfiguration as well as high level plug & produce, plug & participate and concurrent work skills. Novel ICT services required by manufacturing differ from general IT-services. The main points, which highlight manufacturing, are interaction ability; powerful functionality (manufacturers will want to streamline business processes and to optimize inventory), real-time ability and multi corporation set up.

More standards on all levels will be defined, most likely on international level and done by institutions outside of manufacturing science (information science). Implementation decisions are rather a matter of choosing and evaluating than developing own standards, or engaging in standardisation organisations. It is always worthwhile to keep an eye on rapidly spreading devices of telecommunication and respective freeware for general use that could eventually establish irresistible quasi- or de facto standards. Manufacturing near associations ought to provide recommendations which existing or upcoming standards should be considered.

Many virtualization instruments address manufacturing

main processes, hence key productivity issues (e.g. cloud). The use of resources along these virtual models will translate into lower costs for all involved units. Early adopters of such novel DM options might immediately establish so far unseen KPI benchmarks and cause high competition pressure. Specialization of manufacturers using complex and expensive machinery or factories to develop certain products or sub-products for other manufacturers is facilitated. Moreover these systems might instantly demonstrate drastic changes in the forms of manufacturing or manufactured products and, especially, could initiate novel business models synthesising new services and new products. Especially, Cloud Manufacturing allows easy integration of applications and processes both within an organization and between different organizations that wish to collaborate. However, some of the greatest concerns are security problems, loss of control (infrastructure, services, and management), technology, difficulty in migrating to other platforms, and loss of reliability. Companies may feel most attracted to the hybrid cloud, an option that might be reserved for applications, which do not require any synchronization or highly specialized or expensive equipment. Initially, hybrid solutions with large portions of proper company implementations are expected.

Additional machine capabilities will completely and rapidly change manufacturing all over the globe. Wireless communication, powerful online identification and localization devices have been successfully integrated in manufacturing already; now novel upgrading functionalities are introduced to the shopfloor. There is certainly much more to come, especially if we imagine implanted or embedded processors in practically any object and any piece of equipment. Mechanisms can be implemented for virtually composing products or for intelligent components finding each other on the path to value creation. Powerful and efficient applications, available as cyber physical systems, as Internet of things, pervasive computing or machine to machine communication will make DM a preferred model to produce.

Wireless technologies will further strengthen telecommunications' involvement in manufacturing. This tendency has just started to gain ground by the introduction of efficient tracking systems in synthesis with cloud computing solutions. Manufacturers of computer hardware as well as software vendors will have to take into account this virtualisation of resources. After some reluctance of leading software providers to offer these upcoming services e.g. cloud, impressing solutions have quickly changed attitudes. Software as a service, infrastructure as a service etc. are fully integrated in important software service programs. Anything as a Service (AaaS) could be the wording anticipating more upcoming options. Additional equipment features, such as awareness, autonomy, modularity, scalability and networkability will step into the manufacturing thinking, which might be called smart DM. Management should be aware of upgraded machines and manufacturing equipment, orders and products, parts and pieces. Networkability will gain utmost importance on all levels, be it for all KPI's on all levels, additionally introduced network ability parameters or network rules. Management

could get prepared for situations where network ability and alignment parameters have higher priority in comparison to traditional KPIs. Moreover, management should be aware of alternative network configurations at any time and have evaluations ready. Time and history will, in most cases, inhibit to switch to the optimum network configurations. It will only be possible with some delay. Nevertheless all alternatives should be prepared as plans, ready to be activated, as soon as the implementation situations occur. Companies should continuously question their strategies. Business models are jeopardised and constantly flowing, key competencies keep repositioning. Pressure will come from companies, taking higher risks in outsourcing ICT, as the advantages are amazing.

Important studies from renowned institutions indicate rationalisation effects that could cut the workforce in industry down to 50% within the next 10 years. The remaining half will have skills that differ from today's qualification schemes [27]. Man machine interfaces and models of employee involvement have always been hot research spots and will continue to provide a plethora of problems for intensive actions. However, progresses in Body Area Networks will simplify many discussions. The tendency shows a clear development towards a strong involvement of digital natives on all levels and in all sectors of industry. The shopfloor will be the domain for digital experts, placing emphasis on developing IT skills and new-media literacy. Observing important players from telecommunication, hardware makers, software designers and systems integrators and the innovation power behind, it is obvious that there will be more intriguing innovations ahead. All controls of machines, robots and other equipment may easily be upgraded for emulating all capabilities and functions in order to ensure full IP interoperability. Multi-agent systems navigate units using polling and negotiating functionalities in order to build up optimal process sequences. Ever-increasing portions of manufacturing will become information, further optimising resources' consumption and instigating the reuse of material as well as the after-use of products. Companies will have to prioritize the upgrades their equipment and will have to take "smart" investment decisions on new machines. The melting of key information technologies with manufacturing resources is only at the beginning of an era; the first humanoid robot, able to replace humans on the shop floor in large scales, is expected to appear, latest by 2025.

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Operation and Automation IFF, Magdeburg. Since 1995, Prof. Dr. Kühnle is the speaker of the research field „Advanced Production systems in Saxony-Anhalt“ and board member of several companies and venture capital groups. From 1980 to 1994 he worked for Fraunhofer Institute for Production Engineering and Automation IPA in Stuttgart, on Material Flow Planning, Enterprise Planning and Organisation, Computer Integrated Manufacturing, since 1991 as Research Director and Head of the division „Enterprise Planning and Control“. During this period he initiated and built up and managed the “CIM-Technology Transfer Centre” for the University of Stuttgart. Moreover he was in charge of the Management of a number of international, national and regional research programmes and projects as well as successful research projects with leading national and international companies and partners in research and industry, supporting innovation for company restructuring and start ups. He is author of numerous editions, publications, lectures notes and congress contributions.

**Hermann Kühnle** joined the Otto-von-Guericke-University of Magdeburg as a Full University Professor for “Factory Operations and Production Systems” and Executive Director of the Institute for „Ergonomics, Manufacturing Systems and Automation“ in 1994. From 1994 to 2001 he also was Foundation- and Executive Director of the Fraunhofer Institute for Factory