Contents lists available at ScienceDirect

CIRP Annals
Manuf. Tech.

J. homepage: www.elsevier.com/locate/cirp

Cooperative and responsive manufacturing enterprises

J. Váncza[a, b] (1), L. Monostori[a, b] (1), D. Lutters (2)[c], S. R. Kumara[d] (1), M. Tseng[e] (1), P. Valckenaers[f], H. Van Brussel[f] (1)

[a]Fraunhofer Project Center on Production Management and Informatics, Computer and Automation Research Institute, Budapest, Hungary
[b]Department of Manufacturing Science and Technology, Budapest University of Technology and Economics, Budapest, Hungary
[c]Laboratory of Design, Production and Management, University of Twente, Enschede, The Netherlands
[d]Department of Industrial and Manufacturing Engineering, The Pennsylvania State University, USA
[e]Department of Industrial Engineering and Engineering Management, Hong Kong University of Science & Technology, Hong Kong
[f]Department of Mechanical Engineering, Division PMA, Katholieke Universiteit Leuven, Belgium

Abstract: The paper discusses manufacturing enterprises' compelling challenges that are directly stemming from generic conflicts between competition and cooperation, local autonomy and global behavior, design and emergence, planning and reactivity, uncertainty and a plethora of information. Responses in product and service design, organization of production networks, planning and management of operations, as well as production control are surveyed. As illustrated through industrial case studies, production engineering should integrate a rich body of interdisciplinary results together with contemporary information and communication technologies in order to facilitate cooperation and responsiveness that are vital in competitive, sustainable manufacturing.

Keywords: Production, Coordination, Responsiveness

1. Introduction

Enterprises always operated within the fabrics of economy, society and ecosystem. However, in the past decades, the landscape of industrial production dramatically changed characterized by increasing customer expectations that require shorter delivery times, customized and personalized products and extremely high service levels. There is a general consensus of scholars and practitioners alike that the ruling feature of production in this complex environment is *change*. One may envisage a future with ever increasing rates of change: greater variance in demand, business, organizational and technological options, greater uncertainty in responses to complex socio-ecological systems. Changes redrew the map time and again in *production engineering* research from the very inception of the field. This paper adds a new path to this map that is based on the study of another, emergent feature that shapes the conditions of production in a fundamental way: the increased connectedness, speed and scope of technical, economic and social *interactions*.

1.1. Responsiveness in production

Manufacturing science detected early, in fact almost immediately with the first wave of the spread of information technology, that the ability to respond to changes in time is a matter of survival [69]. During that period enterprises excelling in highly optimized decision making and the most advanced information processing technology of the day could also fail, just due to the lack of responsiveness. In this short upsurge of activities, the fully automated, man-less and lights-out factory worked well under known conditions, but failed when unexpected situations called for human intervention and interpretation, insight, conflict resolution and compromising [71].

Responsiveness is a generic requirement in production engineering, a continuous quest for solutions that work in reality and under changing conditions. Responsiveness is a repeated effort of mapping projections of the future (i.e., plans) to actual developments and actions in the real world. It has a number of manifestations in all main engineering functions, from product design to the monitoring and control of manufacturing processes and systems. Responsiveness is one of the cornerstones of intelligent manufacturing [70], resilient [69], adaptive [101], biological [197] and fractal manufacturing [213]. It is an essential element of flexible [84] and reconfigurable [95] manufacturing that provided the necessary technological foundations. Agile manufacturing considers changes as opportunities and stresses the technological and organizational conditions of fast reaction time [42]. In the holonic manufacturing framework PROSA where the role of planning is reduced, responsiveness becomes the central concept [200][203]. Product lines are nowadays dynamically adapted to changing market environments [28], while responsiveness is an underlying idea of changeability [218], and also of the SPECIES framework capturing the co-evolution of product, processes and production systems [187].

Responsiveness is a generic property that includes the capacities of a system to react to external changes by appropriate transformation of behavior or even structure (*adaptation*), as well as to withstand the influence of disturbances without essential changes in the system's behavior (*robustness*). It implies ongoing interaction with the execution environment and requires that the environment could be at least partially *observed*. Among other issues, this calls for the *identification* of objects, as well as the *monitoring* of their behavior, either in the real or the virtual world. Responsiveness is also a human quality that implies an emotional, interactive relation to people and events which may have an essential role when it comes to coordinating the use of common goods and resources.

1.2. *Cooperation in networked production*

Where system components interact with each other, like in a *network*, a special opportunity appears to tackle the various forms of *incertitude* which can be broadly classified as uncertainty, risk, ambiguity and ignorance. This is called *cooperation*, an interactive relationship that makes it possible to harness knowledge of other system components or to make use of their actions in the service of joint interests. The basis of any form of cooperation is reciprocity and trust between autonomous parties who can decide and act in their own right. *Autonomy* refers to freedom of will and the ability to exercise this will: it provides the ability to generate individual goals given some motivations, to select goals to achieve from alternatives, as well as to decide on the adoption of others' goals. Cooperation is the alignment of various, possibly even disparate goals in the hope of some mutual benefit. Cooperation can be developed among interrelated parties who have their own identity and discernible interests (expressed in terms of goals, objectives, utility or profit, etc.); who have the faculties for pursuing their own interest, and who admit to the autonomy of other, related parties. Cooperation has a number of forms in the physical and biological world, and is the prime basis of processes, organizations and institutions of human society [12].

Returning to the narrower context of *production engineering and management*, the point of departure is that operations of any enterprise are carried out in interaction with the market or consumers, market competitors and suppliers, technology and service providers, as well as with authorities and agencies that all define the environment of business. Of particular interest here are relationships with other autonomous partners (also called agents). To complement the division of labor between parties like this, *coordination* is essential for synchronizing actions for achieving some common, system-wide goals (hence, often the term collaboration is used). In turn, coordination is rarely possible without information exchange, i.e., *communication*. As noted above, incertitude is a main driver for cooperation, the resolution of which calls, again, for communication. *Information processing and communication technologies* (ICT) are not only enablers of coordination and cooperation, but they also shape the possible forms of these relationships.

1.3. *Structure of the paper*

In what follows the paper first briefly discusses the trends that shape the present and future of economy and technology (Section 2), defines the scope of investigations (Section 3) and, by taking the production engineers' perspective, identifies compelling challenges of networked enterprises that consist of autonomous entities (Section 4). Next, contemporary responses to the core challenges occurring in the main relevant fields of production engineering such as (1) innovation, product and service design, (2) organization of production networks, (3) planning and management of operations, and (4) production control and execution (Section 5) are presented. This *state-of-the-art review* is followed by a survey of relevant approaches of other disciplines (Section 6) and methods of contemporary ICT (Section 7) that are especially relevant to the topic of the paper. Resolutions to some challenges are provided in Section 8, while Section 9 is devoted to *industrial case studies* that highlight some elements of these resolutions. It is concluded that faculties of cooperation and responsiveness are indispensable for making competitive and sustainable manufacturing a reality.

2. Current trends

Global networked economy

The global economy sets the stage for enterprises where they compete not only individually, but also as members of various networks. In fact, enterprises assume typically multiple roles in a network (e.g., buyer and supplier), and may participate in a number of networks at the same time. Taking a strategic view, one can make a distinction between *efficiency networks* which focus on some form of efficient performance, *globalization networks* which aim at reaching new, emerging markets and *knowledge* or *innovation networks* where the objective is facilitating innovation and developing new knowledge [118].

Responsible and sustainable economy

Enterprises have to respect not only their customers' and their own interests but also those of other stakeholders, including the social and natural environments. Hence, they have to take a socially responsible and sustainable approach and be conscious of the parsimonious use of material, energy and human resources [85]. In fact, one has more than proper resource management at stake here: enterprises must learn to look at ecological systems as fundamental life-supporting services (like provision of crude oil, purification of air and water resources, detoxication and decomposition of waste, etc.) of human civilization. There is a call for a new social contract for science [107] that needs to be addressed by the scientific community of production engineering, too. Yoshikawa [225] and Jovane et al. [85] analyzed already diversified requirements for sustainable manufacturing. According to the generally accepted notion, a *sustainable* world is economically feasible, ecologically sound and socially just [76][107]. The crux of sustainability is whether one violates the limits of what can be referred to as the *human condition*. Taking this stance in the context of production engineering, a poor design is unsustainable, just like the operation of a factory emitting tons of carbon dioxide, or a supply plan that sends parts and components on a world tour before final assembly, or an inventory policy resulting in stocks of obsolete inventory.

Value systems

Organizations—enterprises included—make increasing efforts to define their value system and derive their actions from their stated value. The value systems that are complex and heterogeneous have the following typical elements [215]:

- *Core values* such as integrity, honesty, respect, image, and reputation.
- *Created values* that are consequences of operations, like profit, return on investment, service level, etc. Created values embody the reason why an enterprise exists.
- *Protected values*: conservation of natural resources, and workforce well-being.

While created values were always of prime interest for production engineering, the importance of the other types of values has also recently been recognized [163][196]. One is witnessing a transition towards focusing on value-adding activities and justifying their underlying decisions, though it is still open how to harmonize different types of values in case of conflicts, as well as how to make core and protected values operational during production.

Personalized production and value co-creation

The next manufacturing paradigm points in the directions of *personalized* [94] and *co-creative* production with an increased role of the customer in the value creation process [196].

Customers are involved in the production from the decisive moment of the conception of ideas, already in the design of the product they are going to purchase. With the pervasive connectivity of the Internet, personalization has been increasingly adopted for consumer products. As opposed to customization which emphasizes on meeting explicit requirements of defined market segments, personalization aims at effectively and efficiently satisfying individual needs based on implicit requirements and self-identity expression [190]. Furthermore, customers purchase products for solving their problems and achieving their goals, rather than for the products themselves. Hence, enterprises must offer a combination of products and *services* [196], leading to *industrial product-service systems* [121].

Overall connectedness and computing

Novel information and communication technologies provide information channels for interlinking both enterprises and their customers. These channels are the main technological enablers of globalization [94]. At the same time, this new potential also increases the need for fast action (and reaction) by actors in the economy. Since ICT allows members of a network to widen their span of interest and control, the distribution of information and decision rights introduces some new elements of uncertainty that can be resolved only by appropriate mechanisms of information sharing and cooperation. ICT services will invisibly pervade into everyday objects and environments, and will increasingly conform both to the person of the user and the context of their use. These situation dependent services are originating in a digital world, but are perceived in the physical world.

3. Scope of investigations

The problems of cooperative and responsive manufacturing enterprises can be tackled and analyzed along two main cycles of production engineering (for a simplified view, see also Figure 1), which are the

- product-oriented or development cycle,
- production-oriented or demand fulfillment cycle.

The *product-oriented* or *development* cycle involves the following functions: innovation and product design, planning of production processes as well as the organization of production resources (suppliers included) that are capable of delivering the product. This cycle is essentially about objects—products that could be artifacts or services, product lines and portfolios, production capacities and equipment, systems as well as networks. Main interfaces with the customer are the *design* and *sell* functions where requirements are articulated and fulfilled, respectively.

The *production-oriented* cycle concerns questions of how to produce what is needed and to deliver the right amounts at the right time with the right quality. This demand fulfillment cycle involves main functions starting from supply through actual production, delivery and sales—functions all related to the behavior of production systems. Hence, this cycle is mostly about planning (i.e., the design of behavior) and execution of demand fulfillment activities. Due to the high complexity and uncertainty embedded in manufacturing systems, these functions are traditionally realized on several levels of aggregation, time planes and horizons [59][176]. On the *strategic* level, long-term functions such as sales and operations planning decide on business goals and governing policies, while on the *tactical* level decisions focus on achieving these goals by advance planning and the coordination of logistics and production operations. Here, the essential activities are planning of supply, inventories, production and delivery on a medium-term time horizon. Finally, on the *operational* level detailed scheduling of logistics and production activities are dealt with in the short-term. In addition, a near-time control is responsible for executing the schedules and reacting to unexpected events at the time of realization. The production-oriented cycle can be closed by re-use. Naturally, as it will also be discussed later, the two basic cycles are strongly dependent and interlinked in a number of ways.

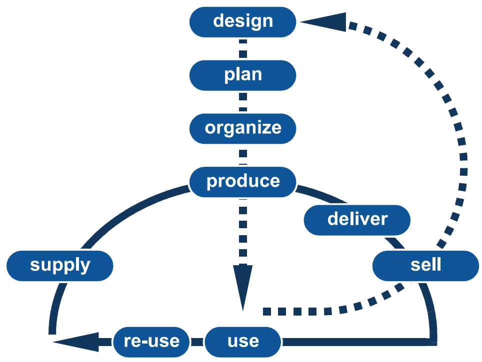

Figure 1. The innovation/development cycle (dashed line) as well as the demand fulfillment (full line) cycle of production engineering.

The above functions can be realized in a complex and embedded *structure* as shown in Figure 2. This overall scheme highlights that various customer demands have to be met in a timely manner, each on its industry and business specific time plane. Customers or groups of them—even if they do not anticipate this—face with their demands a network of enterprises. The structure of the network is defined by autonomous production nodes and logistics links (A). Each node has its own internal decision mechanism, typically on various levels of aggregation, from long-term sales and operations planning via medium-term production planning down to production scheduling and control (B). Finally, each node has its own execution mechanism where plans are realized on the shop floor (C). These three main levels—network, enterprise and shop floor—define a layered decision scheme where targets are set hierarchically, in a top-down way. On all levels, responsiveness requires timely decisions, though the timescales are consistent with the appropriate level. It is also essential to respond both to new or altered demands (coming usually from an upper level) and changes and disruptions (feedback from a lower level). Disturbances coming from the environment (different on all levels) are represented in Figure 2 by lightning bolts.

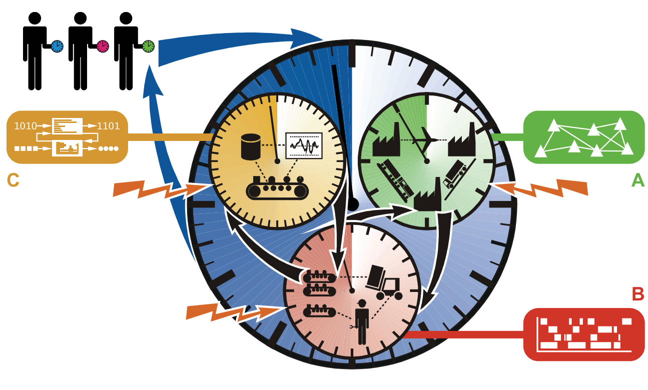

Figure 2. Overall structural view of cooperative and responsive manufacturing enterprises.

In summary, the scope of the paper encompasses *cooperative and responsive manufacturing enterprises* (CoRMEs) that form *production networks* where *autonomous* enterprises are linked by relatively stable material, information and financial flows [219]. The enterprises contribute value in a chain that results in artifacts and, optionally, related services. The members that are cross-linked by ICT systems are not only able but also willing to interact with each other, i.e., exchange information about their products, intentions (plans), expectations (forecasts) and status. An open and overlapping network structure is assumed, i.e., enterprises may belong to several networks at the same time. The model of CoRMEs embraces also customers or their groups. The discussions will refer to issues typical to the discrete manufacturing sector.

4. Challenges for cooperative and responsive manufacturing system

Current trends pose some novel requirements for manufacturing, which are—as in the case of all really difficult engineering endeavors—hard to reconcile with each other. These issues are discussed by taking two typical stances: a conservative, skeptical, more cautious one versus the utopian, optimistic standpoint. Departing from the main cycles of production engineering (see Figure 1), these compelling requirements are discussed in the following domains:

- *innovation*, product as well as service *design* and *engineering*;
- *organization, network design* and *governance* that substantially define the structure and the ways of interaction in productions networks, while *communication* relates the content and protocol of information exchange between networks members;
- *decision making*, *planning* and *management* that are to be performed locally at the network nodes; and finally
- *execution,* including production control, monitoring, performance evaluation and feedback.

4.1. Innovation, design and engineering

According to a generic approach, as for managing market uncertainty and variability of required products and services, accepting the complexity of the market is not really a choice but rather a necessity [190]. The opposite opinion states that the only way to make the future predictable is if one takes part in its creation. This calls for co-creative decision making [196], or in short *co-creation* as a new design paradigm. Accordingly, by means of novel business models and with the technical support of universal connectivity, engineering design should get into the core of production [191]. Customers should no longer have a passive role; they should participate in the value creation process through what is called an experience environment [13][150]. This is of special importance in service engineering where customers interact with the operations [11]. However, if various stakeholders participate in the process of constructing products, design is not a clear-cut engineering problem that can be solved by functional decomposition anymore. There is a need for a socio-technical framework that admits the different perspectives of stakeholders, emphasizes interaction instead of iteration, makes the conflicts rising in the course of the design process explicit and strives to achieve acceptable trade-offs via negotiation [106]. Questions such as whether to accept or shape demand lead to the deep-rooted issue of value in society: according to the traditional view, the market is the place for determining and exchanging value, while co-design says that value comes from interaction with the product.

The conventional strategy for facing increased demand variability calls for product *modularity* and *standardization*. This way, enterprises create a technology landscape that is easier to navigate and, due to better predictability and economies of scale, cheaper to work on. But is predictability really so worthwhile? After all, this approach makes it easier to track and copy products, puts products and practices into molds and undermines the innovation process. As an alternative, *customization* and *personalization*, in which customers are offered much larger design freedom to satisfy their diverse needs with their personal involvement, require an elevation from the module-based configuration techniques [190]. However, it is open whether and how the underlying production and logistics functions that were prepared to meet exogenous demand can operate with a comparable efficiency. Complexity and spiraling costs can easily impede customization efforts.

The process of *innovation* is, as Arrow expressed, “virtually by definition, filled with uncertainty; it is a journey of exploration into a strange land” [6]. In a networked setting this is not a lonesome journey. With the transition towards global networked enterprises, governmental regulations are needed to adopt common principles for arranging flows of information, handling intellectual property rights, and taking other regulatory policies in commerce [94]. However, no regulations can substitute for *trust* that should be developed and maintained between enterprises operating with different value systems, business practices and cultural traditions. Today, innovations in business models and processes are at least as important to production as product innovations were in the past [9].

4.2. Organization, governance and communication

Sustainable manufacturing regards social-ecological systems (SESs) as capital assets that have value in the conservation of options. Unlike other common forms of capital (production capacities, inventories, etc.), SESs are, however, typically poorly understood and inadequately modeled. The importance of SESs is often realized only after they undergo irreversible degradation, upon their loss [36]. There is an urgent need of (financial) incentives that reward the proper management of such assets. However, as noted above, ecosystems provide not only resources but also life-supporting services. Because these services of SESs have no economic markets, their supply is scarcely monitored and there is no real feedback of the changes—typically, deteriorations—of the underlying systems that provide them [224]. It is also open how these incentive mechanisms should be combined with the traditional ones related to created values, without decline in productivity, profitability, and competitiveness.

The *organization* of production networks involves the selection of suppliers, the assignment of products to suppliers, the location of production nodes as well as the design of the distribution system. All these decisions set the channels for the flow of materials, information and financial assets within the network. It is a fundamental scientific and engineering attitude to optimize these structures and flows, as far as possible [37]. The usual criteria are cost, service and inventory levels, and recently, flexibility [174] and changeability [218]. Though, in lack of any central agency (or a powerful dominating partner) how a network can organize itself is problematic. Considering open network structures and a multiplex role of partners in several production networks—which is rather the rule than the exception in industrial practice—the idea of holistic optimization is doubtful [21]. Open, overlapping and polycentric networks cannot be optimized because there can be no aligned business objectives, no common agenda, and after all, no closed solution space. These are Class II and III problems, according to the categorization by Ueda [195]. Production networks should be carved out from a rich fabric of relations, but who would decide on the scope of modeling? How should one extend the range of logistics and production management beyond the limits and restrictions of ownership? Production networks are not designed but come into existence; how can this process be modeled, driven and controlled?

Acting together in a cooperative way can only be an *emergent* property of the overall system. However, in an enterprise network, emergence can just be an obstacle to the practical deployment of decentralized solutions. Industry needs both guarantees for the emergence of some useful properties (like high service levels) and safeguards against unwanted behavior [130]. In fact, there exists a wide spectrum of suggested *interaction mechanisms* between enterprises, from the rigorous transactional models that work through legal terms and contracts up to the relational mechanisms that rely on moral control, informal exchanges and cooperative attitude. However, one may have opposing views on what a mechanism is worth applying when setting up bilateral (typically, buyer-supplier) links [105].

Any kind of communication requires not only a common understanding of the language and protocol used, but also of the conceptual reference model behind. For a computerized information exchange, a formal representation, a kind of enterprise ontology is required [39]. In an open, decentralized setting it is far from being evident how the partners may arrive at such a common basis of communication. As an alternative, the mapping and/or merging of local ontologies must be solved [38].

4.3. Decision making: planning and management

While any network as a whole is driven by the overall objectives to meet the customer demand at the possible minimal production and logistics costs, the efficiency of operations and the economical use of material, energy and production resources hinge on the local decisions of the partners. The issue is how to achieve and maintain the right overall behavior of the whole network if the autonomous business partners decide locally, based on *asymmetric* and partially *incomplete* and *inconsistent* information. What would drive any partner to scarify some of its own goals in the hope of an eventual mutual benefit?

The basic setting of networked production where decisions are made autonomously at the nodes implies a *decomposed* scheme. Naturally, so as to satisfy demand, decentralized decision making has to be *coordinated*. According to the most common scheme, this should be done in a top-down, hierarchical way. In the course of so-called upstream planning, starting at the downstream party (e.g., original equipment manufacturer, OEM), local planning problems have to be solved in a sequence where the solution of one problem sets target for the next one. The inevitable sub-optimality of the decomposition approach calls for *centralized* supply chain planning methods [103]. The centralized models are of great theoretical relevance, but they may only be applied if the parties are strongly tied together, e.g., they are different divisions of the same enterprise or constitute a *virtual enterprise* [33]. The potential loss from decentralized versus centralized decision making in supply chains can be referred to as the price of anarchy [147]. The key question of *coordinated planning* is whether it is possible to decrease this price, to circumvent the deficiencies of the decomposition method when there is no opportunity for centralized planning. Can one improve the overall performance of the supply chain, while maintaining information asymmetry and local decision authority of the partners?

In order to achieve and maintain a right system-wide behavior of the network, information sharing and coordination in themselves are not sufficient: a *cooperative attitude* of the partners is also needed so that they can resolve their eventually conflicting individual interests. However, may anyone suppose, as it is the foundation of many models, that partners are inherently benevolent? Or instead, should the partners be made interested in cooperation? Is there any other way to come to cooperation except by sharing risks and benefits? Can eventual short-term losses be compensated on the long run? Returning to communication, may one assume that partners in a supply chain exchange all relevant information about their actual status and future plans truthfully, or, just in the other way around, bias, distortion, even deception may come into play also here? Can repeated successful encounters provide opportunity for trust building that is the basis of most forms of cooperation?

In planning, *time* is of the essence. As discussed above (see Section 3), planning goes on over strategic, tactical and operational levels, on corresponding time planes and horizons. Demand and supply mismatches of which operational level component shortages are the most common type, can closely be associated with significant drops in performance, as far as income, return on sales, and return on assets are concerned [75]. To avoid this, as a characteristic interpretation of responsiveness states, decisions have to be made more and more in *real-time*. However, this increased reactivity blurs the traditional hierarchical decision scheme: a response to some glitches on the operational level may have substantial repercussions not only on the tactical, but also on the strategic levels of decision making. Violating the isolation of decision time planes inevitably results in additional complexity.

Planning concerns decisions about future courses of action that are mostly based on expectations (e.g., demand forecast, resource availability, and material supply). Planning is indispensable in having sufficient foresight for optimization (of service level, costs, material usage, etc.), and in forming *intentions* that can be communicated to other related partners. In fact, efficient local planning resulting in executable, cost-efficient and stable production plans and schedules is the key to predictable behavior. Unfortunately, today's advanced planning and scheduling (APS) systems are still seen as unusable, or as unable to handle the complexity of the underlying capacitated planning problems, let alone uncertainty in demand, or in resource and material availability [149][176]. In planning, responsiveness involves the ongoing matching of plans to reality. Repeated planning on rolling horizons mitigates this problem, though changes in the plan(s) of any partner can easily proliferate through a network and initiate re-planning at other nodes, causing a domino effect and system nervousness. To avoid this, *robustness* is a primary requirement for local planning.

4.4. Control and execution

In an unpredictable environment, there exists no fixed problem statement for production control that needs to be addressed once. Instead, one has to handle a stream of information about the underlying enterprise—forecasts, state information as well as communicated intentions—while the monitoring and control system should constantly take actions to influence the system's behavior. This activity has no predetermined ending. The actions must keep the enterprise in a safe state and aim, at the same time, to optimize its performance, according to some ever-changing, actualized criteria. The monitoring and control systems have to balance immediate performance optimization against future stability and maneuverability.

Even when working with deterministic plans and schedules (as is the typical case) in an uncertain environment, the need for change should be anticipated as early as possible. This calls for the application of *predictive* techniques using simulation [126]. When the models accompanying production resources include a capacity reservation system, virtual execution may account for the expected loads and near-future conflicts amongst prospective users. This may result in a proactive, model-predictive control that goes beyond stochastic methods [200].

Monitoring, evaluating and making the performance of individual partners public is an essential prerequisite of cooperation that should be based on reputation and trust building. Performance evaluation is typically done in a hierarchical setting when a powerful, dominating partner—e.g., operating in the focal point of a production network—measures the performance of its suppliers [207]. However, who is in charge of this in a completely decentralized system?

Tracking and tracing methods involving the automated retrieval of the *identity* of objects makes possible the complete monitoring of items that move through a value-adding chain [216]. *Auto-identification* techniques facilitate the storage, retrieval and communication of accurate, timely information about items. This information should be fed back to decision making and control functions. The notion of *intelligent product* encompasses the permanent linking of information and material contents as well as the decision making capability of the product itself [119]. Coping with uncertainty and lack of information in this way is only one side of the coin; different, though equally hard problems ensue from the *plethora* of information. When preparing the foundation for informed planning decisions, enormous amount of behavior related—i.e., dynamic—data must be handled, synchronized, cleared, filtered, aggregated and archived [207]. The decision complexity of planning processes can only grow with the expansion of input data, which is in sharp conflict with the requirement of giving timely, almost instant solutions [207].

5. State-of-the-art: production engineering's perspective

5.1. Innovation, product and service design

In production networks, design goes beyond the boundaries of classical engineering design [188] and is interleaved with strategic marketing and network organization issues. Products should be clustered according to variables like demand and supply uncertainty, lead time or economies of scale [153][174], defining a matching business model, as well as finding the right interface between customer-anonymous and customized production along the demand fulfillment cycle. While the latter points are discussed in Section 5.2, below the engineering aspect of design is discussed only.

Modularization, product line design

Yoo and Kumara propose a cyber-infrastructure for *modular design* that not only configures products but suggests a limited set of solutions that are optimal according to given criteria. In global manufacturing, this method can leverage a digital design repository of modules actualized continuously by the suppliers [223], a situation typical, for example, in the low-cost computer industry. Seliger and Zettl analyze modularity in the context of life-cycle engineering, by defining its ultimate goal to increase product sustainability [169]. Hence, they take drivers for modularity not only from the stages of design and production, but also from use (maintenance) and end-of-use activities into account.

In some early attempts for co-creative decision making, both Tseng et al. [192] and Márkus and Váncza [113] realized the following: when customizing their products, manufacturers attempt to fulfill specific requirements of the customers within the confines of their design, planning and production environment. They elaborated frameworks for *product line design* that captured more technical features of this problem than microeconomy: in addition to customer welfare and profit maximization considerations, engineering aspects also have been made operational. Driven by the interaction between customer preferences and the reallocation of manufacturing resources, viable product families emerged from a variety of technically feasible product alternatives. Chen et al. suggested a method for product line adaptation that is based on an evolutionary approach, and developed an optimization method to find the right compromise between conflicting marketing and engineering incentives [28].

Co-design and co-creation

By exploiting ubiquitous connectivity, an enterprise can challenge the traditional business models by involving customers and other human resources into the design process. The *mass collaboration product realization* method assumes a core design team but harnesses collective intelligence coming from outside of the core, too [55]. Here, a platform and appropriate workflow are also presented that support forming teams, sharing information and executing design tasks in an orderly, though decentralized way.

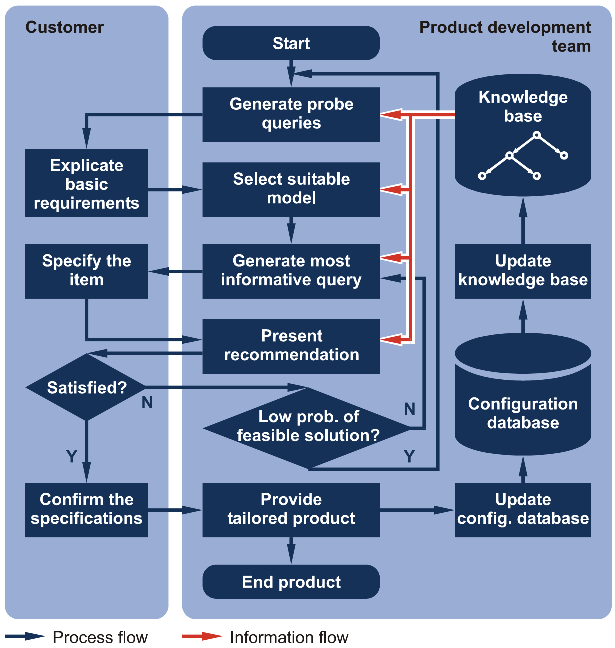

Figure 3. Concurrent engineering with customer preferences [212].

Tseng et al. [189] proposed a co-design approach for companies to communicate with customers about current offerings and help customers express their needs and make decisions. Wang and Tseng [212] capture, specifically, the *customers' preferences* and represent them by a probabilistic graphic model. The model is then incorporated into a concurrent engineering scheme to handle the uncertainty and additional complexity in the interactions of design variables. A product development team carries out the specification process in collaboration with the customers, by guiding them to explore their actual needs in an intuitive and user-friendly way (see also Figure 3).

In contrast, the *mass personalization* framework suggested in [190] takes customers as individuals, with implicit characteristics such as personal taste, traits, innate needs and experience that can be made operational in the course of interaction during the design process. While customization assumes fixed product architectures and design process models, as well as explicitly given customer preferences, personalization goes along a partially constrained trajectory, identifying latent customer's preference and producing perceived unique designs with positive user experience for each individual.

Through what is called an *experience environment* [150], an enterprise may engage its customers in a process of co-creating value [196]. In models like this, offerings of the enterprise go beyond the provision of physical products and involve also sophisticated services. Furthermore, customers may also form communities and interact in a networked environment; the emerging community itself represents a new form of added value.

Services

As noted above, an important trend in production is the integrated, in fact inseparable provision of products and services. Meier et al. give a detailed overview of such, so-called *industrial product-service systems* (IPS^2) that include business models, service design methodologies, and service delivery when actual value is created [121]. Such 'extended products' are, however, highly customized and their value is sensitive to the time of the delivery. *Service engineering* whose actual methods are summarized by Aurich et al. [11] has also to cope with a reality that was earlier foreign to manufacturers: customers interact with their operations. This is the source of a number of types of variability like arrival, request, capability, effort and subjective preference variability [62]. Frei also suggests strategies for managing customer induced uncertainty that result in acceptable trade-offs between cost and service quality. For supporting the design and planning of services, a computer-aided design (CAD) system is presented in [66] that builds on a functional representation of service. This tool helps managers, marketers and engineers alike to improve existing services and design new ones. The service view greatly widens the possible scope of design. For instance, the role of membership service is investigated in public goods problems by using economical analysis and simulation [138].

Information management, ontologies

According to Lutters et al., the process of product creation can completely be captured in terms of the information requirements of the design and engineering processes. Proper information management should be based on a formal representation of the information content, i.e., an *ontology* [111]. Instead of taking a traditional, process centered approach for managing the *workflow* of various tasks (that can be assigned to different actors), design and engineering processes can be driven by the evolution of the information content. So as to realize services that attend the life-cycle of machining and other equipment in production facilities, Harms et al. proposed a *semantic Web-ontology* framework [67]. This is based on a core ontology which is augmented by a number of company and domain specific (development, configuration, etc.) sub-ontologies. Merging and leveraging knowledge of the distinct worlds of design and manufacturing is the crux of *process planning*. In this domain, Denkena et al. suggest combining standard core ontology with a domain ontology that contains company-specific details as for processing technologies, tools, and resources [38].

Innovation networks

Innovation takes place in many of the above approaches in a networked world where some mechanism of collaboration exists between customers and producers, suppliers and end-product manufacturers often even on a global level [9][118]. By discarding the actual details of the relational mechanisms, one can take a holistic view and try to understand where collaboration is present and missing. For such investigations, *network analysis* provides applicable models and methodologies [19].

After having analyzed patent performance of large-scale inter-firm technology collaboration networks in 11 industries, Schilling and Phelps argue that two key structural properties, *clustering* and *reach*, play key roles in the diffusion of knowledge. Networks that have both high information transmission capacity (characterized by clustering), and large quantity and diversity of information (characterized by reach), make innovation really possible at the nodes. These findings concur well with results on what is called small-world networks where cohesion and connectivity make easy the circulation and recombination of creative ideas. At the same time, heterogeneity of knowledge distributed across clusters is the source of diversity in the network, thus it enhances innovation [158].

5.2. Organization, network design and governance

Responsive supply chains are defined as highly flexible organizational structures that are able to respond to changing market requirements in a cost-efficient way [65]. Members of responsive supply chains typically form a virtual enterprise [33], with an architecture optimized for speed, flexibility and costs, with integrated planning, rigorous selection and performance criteria as well as cost management. In fact, supply chain configuration has to handle a wide variety of options because not only the nodes of a chain have alternatives for accomplishing their function but also the location of inventories is an open issue. When setting up a responsive chain, one has to take into account also the availability of alternative capacities and sourcing. The best solution may vary whenever the mix or some features of the products change. The involvement of multiple products in the supply chain and the so-called commonality and differentiability issues make the challenge more complicated [81]. Typically, different products often have common components and associated manufacturing processes despite their distinctive functional features.

Three-dimensional concurrent engineering

The coordination of product design and process planning steps, i.e., *concurrent engineering* (CE), can be regarded as everyday practice. The recently started incorporation of supply chain configuration issues in the traditional CE has been called by some authors *three-dimensional* concurrent engineering (3D-CE). 3D-CE concerns key performance indicators like cost efficiency, time-to-market, quality and responsiveness throughout the whole life-cycle of products [54]. Fine et al. investigated the tradeoffs between what they called *integrality* and *modularity* in product and supply chain design [58]. As for the products, *modularity* refers to subsystems or components whose design or operation is only loosely coupled. Typical products of modular structure are computers or household electronics systems. On the contrary, products that consist of tightly coupled subsystems are *integrated* to a high degree. Interfaces between the components are usually complex, non-standard, and tailored only for a specific product [58]. The architecture of supply chains can be characterized by similar concepts. The members of an integral supply chain are also closely related to each other, as far as location, organization or communication channels are concerned, while the members of a modular supply chain are more dispersed, having fewer and weaker organizational and communication links.

One of the main outcomes of the experiments described in [58] was that the 3D-CE approach resulted in modular-to-modular and integral-to-integral architectures concerning the structure both of products and supply chains. Naturally, the complexity level of the 3D-CE is significantly higher than the 'simple' configuration of production networks or supply chains. However, its benefits are manifested in important parameters, such as reduced product development time, smoother product introduction, quicker ramp-up, lower product cost, increased quality, shorter lead times, and altogether fewer anomalies in the supply chain [17].

A fundamental question is at what stage of the product development process to integrate a supplier (see Figure 4). Early supplier integration—linking product, process, and supply chain design—is considered advantageous if the technology is uncertain. In contrast, a producer can easily be locked into a particular supplier relation this way [148][191].

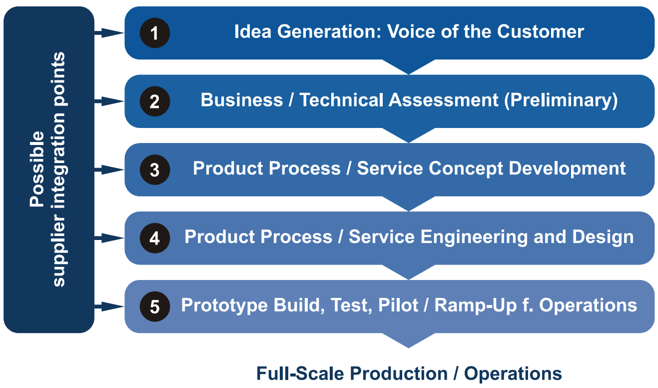

Figure 4. Possible supplier integration points within the product development process (adapted from [148]).

Production networks' structure

Abele et al. and Schönsleben presented a mapping between characteristic features or decision variables, such as demand volatility, supply chain vulnerability, necessity for economies of scale, requirements of consistent process quality, proximity of customers, market specificity of products, customer tolerance time, value density (item cost per kilogram or cubic meter), as well as the structure of production networks, from centralized to decentralized architectures [162]. Figure 5 shows significant correlations between key decision variables.

Production networks, however, are rarely constructed from scratch but rather evolve over time [64]. Hence, the actual structure of a network constrains its future shape. A number of aspects may influence the restructuring efforts, like the maturity of the products, number of products to be potentially relocated, adequate resource capabilities for test runs, as well as ramp-up efforts.

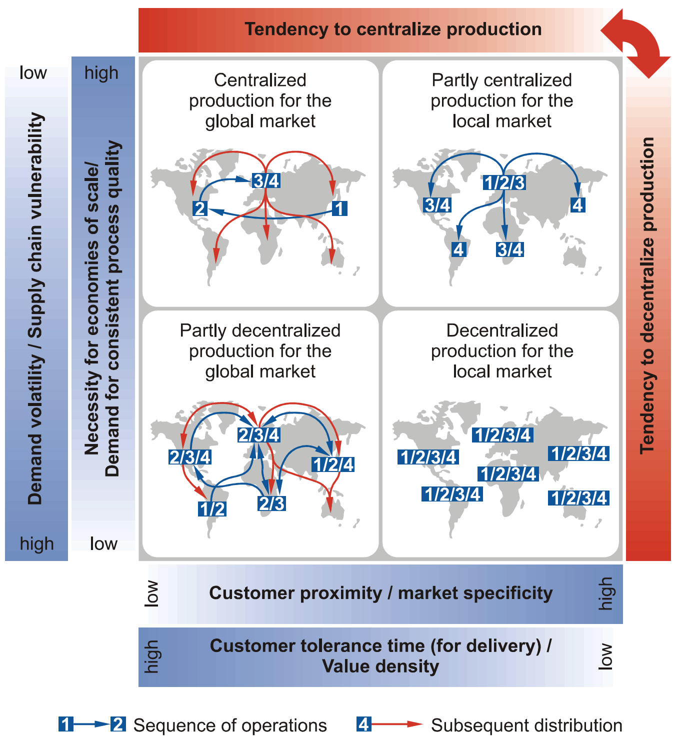

Figure 5. Concepts for production networks depending on characteristic features (adapted from [1] and [162]).

Naturally, issues which influence the complexity and the vulnerability of the network also have to be considered, such as the variety of products produced at a location, the assignment of products to various production facilities, responsiveness to unexpected changes in the environment, exchange rates volatilities, etc. As for an early example of the *resilient supply network*, one may refer to the well-known Toyota case when a strategic level event (fire at the plant of a valve supplier) caused operational level glitches at the manufacturer, who, in turn, in collaboration with other suppliers re-designed not only the supply channels but also the product itself in a couple of days [137]. Going beyond the usual deterministic models of supply network design, Tang gave a comprehensive review of *supply chain risk management* addressing, among other things, uncertain economic cycles and consumer demands, as well as unpredictable natural and man-made disasters [180].

Multi-agent systems (MAS) offer an adequate way of modeling production networks [130] which can be represented by nodes and interactions between them as edges. The dependability—or survivability—of production networks can be investigated from the perspective of *network science*. To be survivable the network must adapt to a dynamic environment, withstand failures, and be flexible and highly responsive. These characteristics depend on both the functionality of the nodes, and the *topology* in which nodes operate [186]. Thadakamalla et al. identified four survivability characteristics related to topology:

- Low characteristic path length.
- *Good clustering*: when two nodes, A and B, are connected, then new edges from A should prefer to attach to nodes connected to B, and vice versa.
- *Robustness to random and targeted failures*: so-called scale-free network and a good balance of critical, not-so-critical, and noncritical nodes.
- *Efficient rewiring*: in case of changing the network structure, the above three components are to be considered.

Some other metrics of topology such as survivability components are described in [19] and [158]. As for representing the topology of production networks, it should be mentioned that a simple (perhaps weighted) graph representation seems to be not appropriate, because the edges between the enterprises can refer to different content like the flow of information, material or money, distances, or transfer times. Consequently, the edges can be treated as vectors, or, from another viewpoint, various aspects of a production network can be represented by different topologies.

Decision support for configuration of supply networks

Huang et al. set up a model for optimizing the configuration of supply chains given commonality among platform products [81]. The mathematical model was solved by dynamic programming and—in order to accelerate the computations—by genetic algorithms. A mixed integer linear programming model was defined for analyzing different relocation options by Grunow et al. [64]. A similar approach was taken by Akkerman et al. for determining the decoupling point of deliver-from-stock and mix-to-order production stages in a food processing supply chain [3]. This work is an example of how product—and especially intermediate product—and production network structure should be designed together, a point also emphasized by the global variant production system design method [211].

As mentioned earlier, the agent-based approach is a natural way of modeling production networks [130]. Five levels of agent-based negotiation from the shop floor level up to the network level are distinguished in [5] and [23]. Each enterprise in the network is considered a software agent with multiple utilities, and a game theoretic approach of negotiation amongst them is proposed in [87]. It was demonstrated that the firms should select negotiation policies based on their management strategies.

Emergence can play a pivotal role when solving difficult engineering synthesis problems. Ueda et al. in their early paper demonstrated that supply networks can emerge as a result of a design process driven by the customers' preferences [198]. Recently, the problem of supply partner selection has been addressed by a novel *quantum-bit multi-agent evolutionary algorithm* [181]. Schuh et al. approached reconfigurable collaborative networks from the aspect of their complexity and developed a methodology for matching the structure of a collaborative production network to the properties both of the environment and products, with special regard to the complexity of these elements [167].

Maropoulos et al. introduced a framework for collaborative design and production network development [115]. The core idea was the parallel and synchronous design and evaluation of the product, the production process and the production network by the synthesis and evolution of four methods: (1) resource aware planning, (2) Digital Enterprise Technology (DET), (3) non-linear control for logistics optimization, and (4) the concept of emergent synthesis. Figure 6 illustrates the three main cycles of the framework:

- *Resource aware planning cycle* where simulated annealing and greedy optimization are used for exploring the huge decision space in terms of selecting processes and generating plans for given design configurations within the network.
- *Network validation cycle* for linking the (digital) aggregate plan from the previous cycle with the (physical) resource characteristics of the network. Here, dynamic optimization methods are used and, by alternating the criteria of demand scenarios, emergent synthesis' Class III problems are treated.
- *DET-enabled, human centric evaluation cycle* for confirming the status of design, the selection of processes and production sites and deciding on the make-or-by options.

The applicability of the framework was demonstrated on the design and manufacturing of complex sub-assemblies from the aerospace industry [115]. This complex approach illustrates how the interplay of different technologies can support the decision making in supply networks' configuration. Digital enterprise technologies—typically simulation—play a significant role here, similarly to other related works [31][100].

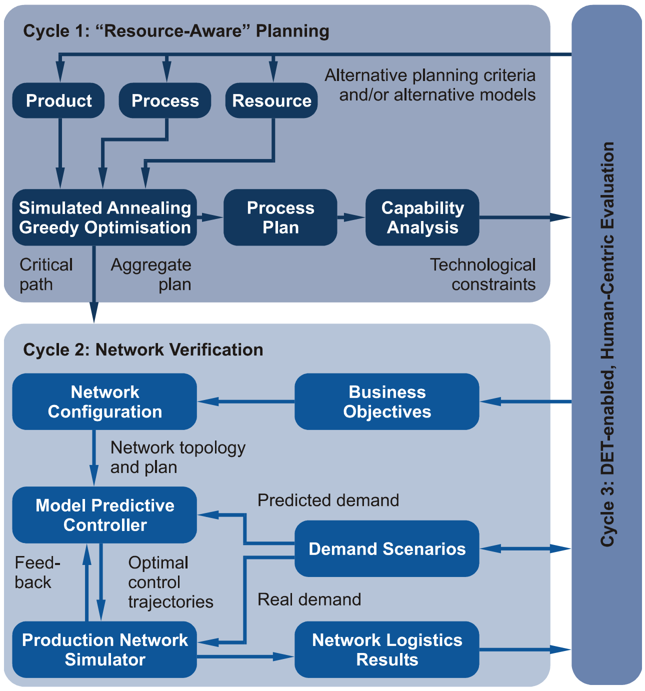

Figure 6. Overview of the framework for the integration of resource aware planning with logistics (adapted from [115]).

5.3. *Planning and management of operations*

Inventory control, logistics

Planning in production networks necessarily crosses the boundaries of the individual enterprise and integrates procurement (up-stream), as well as delivery and distribution (down-stream) decisions. In both directions, issues of logistics, especially the management of inventories, are of crucial importance [182][219] (see Figure 7).

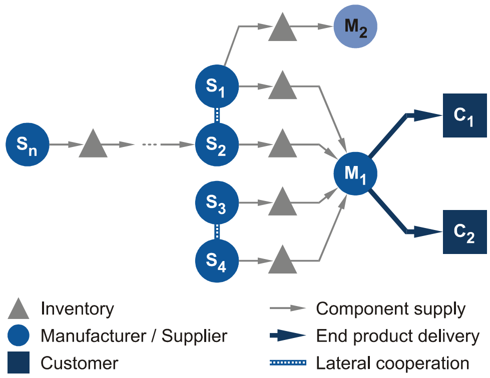

Figure 7. A focal supply network structure.

Inventories, seemingly passive and non-lucrative elements of business can be turned into an efficient means for coordinating networks [29]. Wiendahl et al. call the attention to the potential interdependencies among the performance criteria of various partners and suggest an analytical method for handling conflicting performance indicators such as inventory level, delivery delay and service level [220]. Their method is based also on the so-called logistic production operating curves, suggested by Nyhuis [143].

Channel coordination mechanisms

Channel coordination aims at improving overall supply chain performance by aligning the plans and conflicting criteria of related enterprises [177]. It involves ordering, available-to-promise and inventory planning decisions of autonomous partners. Similar to the well-known prisoner's dilemma, disparate objectives and the decentralization of decisions may lead to suboptimal overall system performance—a phenomenon known as *double marginalization* [185]. Asymmetry of available information and locality of decisions together are time and again sources of acute material shortages or excess inventories. Recently, Albrecht has analyzed and classified a number of drivers that lead to sub-optimality in decentralized planning [2]. In any case, satisfying the target set by one partner incurs some extra costs (by, e.g., too large quantities, or too frequent deliveries required) at another one, increasing thus the system-wide costs.

According to the strong notion of coordination, a supply chain is coordinated if and only if the partners' locally optimized decisions are implemented and result in system-wide optimal performance [2]. This problem can be captured in a game theoretic setting: how to find a set of optimal supply chain actions (i.e., production and delivery) that result in an equilibrium from which no partner has an interest to deviate? The game theoretic perspective leads to theoretical *contract* models [156] that coordinate a supply channel under rigorous simplifying assumptions, e.g., typically, one-period models are handled [25][26][102].

Coordinated planning

There exists a weaker, albeit widely accepted notion of coordination: the supply chain is coordinated if the local, selfish production and delivery actions result in a *better* overall performance than the decomposed solution [44][177]. This definition allows for a broad spectrum of coordination mechanisms that have though some generic features in common:

- While keeping the privacy of sensitive cost factors, the partners share information on their intentions (i.e., plans).
- So as to arrive at a coordinated solution acceptable for all parties, alternative planning scenarios are generated and mutually evaluated.
- An incentive scheme drives the partners—against their local interests—towards coordinated solutions. Typically, potential benefits and risks of coordination are shared.

Based on field research in the American automotive industry, Narayanan and Raman warn that whatever supply coordination method is applied, incentives of the partners must be aligned [135]. Albrecht presents a series of coordination mechanisms that, under multilateral information asymmetry and without the involvement of a third party, identify coordinated solutions and provide motivation to their implementation. The methods are applicable to various types of master planning problems [2]. Channel coordination methods using negotiation protocols iterate over solutions: enterprises exchange proposals and counter-proposals until a mutually acceptable agreement is reached. Hence, this approach is commonly referred to as *collaborative planning* [177]. Dudek and Stadler present a negotiation protocol where two partners exchange orders and supply plans iteratively, arriving at decreased total cost. The savings are shared so as to make the buyer interested in implementing a locally suboptimal plan variant [44].

Risk and benefit sharing

Sharing potential risks and benefits drive cooperation. Of the main risk types supply chains have to face (for an overview, see [180]), *demand uncertainty* is investigated most thoroughly. If acceptable order lead times are shorter than production lead times, high service level can only be guaranteed if production is planned by using demand *forecast*s. However, forecasts are uncertain and in a real network there exists always an information gap between the partners: the suppliers are familiar with the production costs for the components, while the end-product manufacturer can forecast the finished good demand. This demand is distorted by the internal planning processes: normally, master plans are generated which are further refined into production plans and schedules. In the meantime, lot sizing decisions are made and parallel component demands are aggregated. As a result, the actual component demand forecast can hardly be related to the original finished good forecast [207] (see Figure 8). Furthermore, even when actual customer demands are fairly stable, orders often exhibit an increase in variability up the supply chain, a phenomenon known as the bullwhip effect.

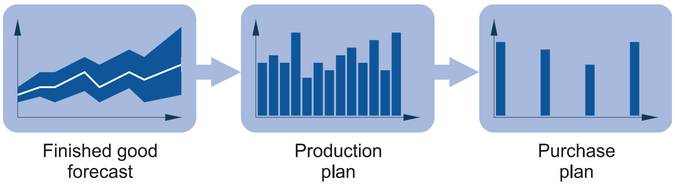

Figure 8. Transition of demand forecasts.

While the general consensus is that information sharing alleviates anomalies in supply chains (for an overview, see [7]), it has only recently been investigated how unreliability, uncertainty and what is more, distortion of information affect the operation of supply chains and networks. The contract models induce autonomous partners to act as if they were forming a vertically integrated virtual enterprise and share the risk of uncertain demand. Such examples are the quantity discount contract, the buyback/return contract and the application of revenue sharing agreements instead of fixed prices [96][180]. While the above models reduce the temporal dimension of the planning problem into a single time unit (and use, consequently, the classical newsvendor model to capture uncertain demand), other approaches take a longer horizon and consider the uncertain and limited life-cycle of stored products due to deterioration or obsolescence [63]. The latter is especially relevant in mass customization that faces volatile demand. Recently, a coordination scheme has been proposed where, based on medium-term forecasts and information about the expected lifetime of a product, the supplier provides a *service* to the customer by committing itself to meet all short-term demand. The price of this service compensates the supplier for the uncertainty of the forecasts, and inspires the customer to improve the precision of forecast and share it with the supplier truthfully [206]. This method minimizes the expected total production and logistics cost and also is applicable on a rolling horizon [208].

Information sharing, transparency

No doubt, all the above coordination methods need—in some cases radically—novel business models and presuppose advanced local decision making, typically planning capabilities. Hence, by taking a more conservative approach, a number of coordination methods have been developed based on existing planning and management systems [157][176]. They all have in common extensive information sharing and communication methods. Some manifestations are the so-called Collaborative Planning, Forecasting and Replenishment (CPFR), as well as the Vendor Managed Inventory (VMI) [177][217]. While the former is based on joint decision making, in VMI the customer delegates the ordering and replenishment planning to its supplier. The supplier can better control the actual production and logistics cost, exploit economies of scale and balance load, but, at the same time, has to face the consequences of imprecise forecasts alone.

Recently, a lot of effort has been made to establish *information transparency* in supply chain control systems. For focal supply networks, Mourtzis et al. adopted the Web services technology [131], while Váncza et al. developed and deployed a so-called logistics platform for sharing planning and scheduling related information between OEMs and their suppliers [207]. Schuh et al. elaborated myOpenFactory, a centralized information sharing agency that is based on standardized, industry-neutral and open data and process models, focusing on order processing and monitoring [166]. Dynamic reconfigurability in a flexible, polycentric network was in the focus of Meier et al. who specifically addressed the requirements of a federation of Small and Medium Enterprises (SMEs) [120].

Robust planning

Coordinated planning requires mastering essential conflict situations. The proliferation and ramification of changes through the network has to be stopped, as far as possible, locally. Hence, results of local planning should be not only executable and cost-efficient, but also robust in the face of changes, disturbances and disruptions. While the requirement of robustness appears in supply chain management on the level of topology (e.g., see [186] for a survivable large-scale supply network), it does not manifest itself in planning. Consequently, appropriate models and powerful solution methods are needed that respect all the main temporal, capacity and material availability constraints and find optimal trade-offs between various costs and due date performance criteria, as well as the robustness of the production plans. On this tactical level, Van Landeghem and Vanmaele identify the primary sources of uncertainty, which are (1) supplier lead-time, (2) stochastic demand, (3) stochastic costs, and (4) price fluctuations, and give a survey of applicable robust planning methods [204].

5.4. Control and execution

The function of real-time production control and execution is to adapt the production system to the changing environment, while preserving efficiency with respect to cost, time and quality requirements.

Information fusion in real-time control and execution

For *real-time production control* an indispensable requirement is the fast collection and presentation of production monitoring data. A factory cockpit system for connecting *real-time monitoring and planning* was presented in [88]. In the solution described in [128] the reference of real-time production control is the optimized, daily schedule. The information about the overall factory is collected in the Manufacturing Execution System (MES) cockpit with a database in common with the production monitoring system and the scheduler. The main database is synchronized in real-time according to changes on the shop floor, and the same mechanism is also responsible for the update process in the Enterprise Resource Planning (ERP) system of the factory. The platform also notifies the users about deviations from the production schedules together with the option to find the cause of the deviation (e.g., raw material unavailability, machine breakdown, lack of operator).

Digital enterprise technologies in control and execution

The concept of the digital enterprise [114] offers one of the prerequisites for supporting control decisions. However, in order to master the high dynamics in the processes and demand, real-time feedback from the production is required [165].

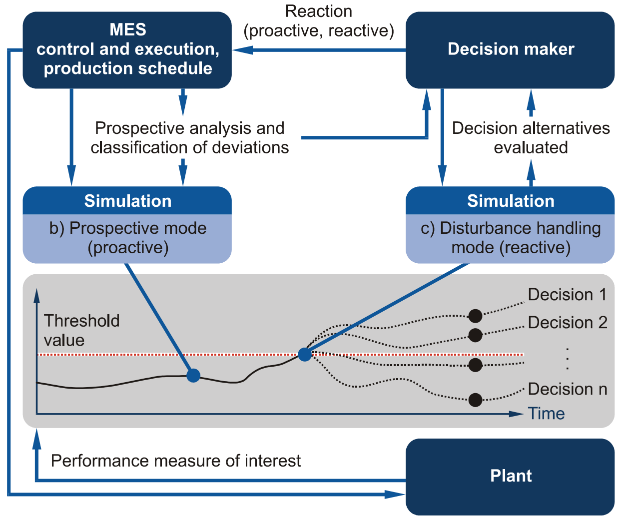

Figure 9. Plant-level active disturbance handling by using reactive/ proactive operation modes of simulation [126].

Parallel to the MES cockpit described above, a simulation module was also developed with the following main operation modes (Figure 9):

- *Off-line validation*, sensitivity analysis of the schedules against the uncertainties prior to the execution (not represented in the figure).
- *On-line, anticipatory recognition* of deviations from the planned schedule by running the simulation in advance for short-term actions. Support of situation recognition; proactive operation mode, denoted as b).
- *On-line analysis* of the possible actions and minimization of the losses after a disturbance already occurred; reactive operation mode, denoted as c).

A more comprehensive approach based on the concept of *grid engineering* was illustrated in [31] where the integration of heterogeneous simulation models, from molecular dynamics simulation and finite element methods up to discrete event simulation, was aimed at. Having answered to these challenges, a tight coupling of the digital and the physical worlds was described in [86].

However, when working with the real-time MES data, one has to face difficulties; the huge amount of information to be handled, and the fact that data is often unreliable, incomplete and false. In [90] an approach was described for extracting knowledge from large, complex, time-dependent noisy and anomalous process logs aiming at producing accurate and detailed routing graphs, statistics and further anomaly explanations. This can help refine models employed by a planning system and reveal modeling or usage issues in production tracking in a factory.

Adaptive shop floor control has to be able to work with a data model that combine product, process and resource related information. Such an open, multi-granular and scalable platform is presented in [202]. The platform that is compliant with the ISO Standard for the Exchange of Product Model Data (STEP) facilitates a bi-directional information flow between the physical reality as well as the management and control of a factory.

Approaches to reactive control

Recognition of changes and disturbances is indispensable for improving customer responsiveness [98]. Intelligent techniques for this purpose and for adapting the production rapidly to current internal and external circumstances were enumerated in [123].

A real-time schedule monitoring and filtering approach based on statistical throughput control for recognizing and evaluating the impact of disturbances was described in [221]. The schedule repair algorithm is activated only in case of severe disturbances in order to decrease system nervousness. Situation detection algorithms and rescheduling policies were treated in [126]. A deadlock-free rescheduling algorithm was introduced in [50].

However, changes and disturbances may necessitate even the modification of the process plans of the workpieces. A new approach for the simulation-supported planning and monitoring of cutting processes was described in [38]. Figure 10 illustrates the main concept: (1) During detailed planning, process simulation verifies the generated process plans and sets the thresholds for measurable, controlled process parameters. (2) Incorporated into the process plan, these values are transferred to the process monitoring system and serve as basis of early warning of risk situations. (3) Experience is fed back into the process simulation and the planning to adjust the process model. As a combination of process planning and process control, adaptive process planning allows for a reactive process control [38].

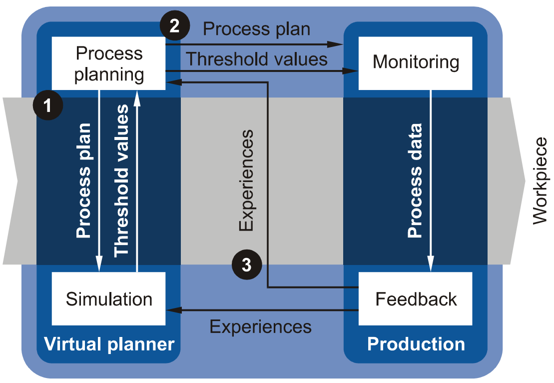

Figure 10. Planning and machining Gentelligent® components (adapted from [38]).

Decentralized control architectures

A dynamic, discrete state-based model for describing production networks consisting of autonomous work systems with local capacity control was considered in [46]. The work systems are represented by transfer functions with inputs like levels of external input and planned work-in-process (WIP), as well as work and capacity disturbances, and outputs like orders, output rates and WIP levels. Experimental investigations showed that WIP level remained close to the planned value, and had variations only due to changes of external orders. With a simple proportional WIP-controller, lead times were kept stable even without any information exchange between work systems. The effect of sharing order-flow information was also examined with the result that only accurate information could hinder the propagation of turbulences to downstream work systems; communicating biased information, in fact, deteriorated the responsiveness of the network [47]. A conceptual framework was presented in [41] for the non-linear characterization of the performance of production and logistics networks in a variety of situations.

General principles of autonomy, including concepts, methods and technologies to realize autonomous processes in *assembly systems* are surveyed in [159]. In this context, scheduling heuristics and autonomous control are compared in [160], and the influence of autonomous control level on logistics performance is investigated in [161].

Emergent synthesis approaches to production planning and manufacturing control in a make-to-order environment were reported in [194]. Distributed, agent-based control architectures offer the prospects of reduced complexity, high flexibility and robustness against disturbances. However, it has also turned out that distributed control architectures, usually banning all forms of hierarchy, cannot approach optimum performance and the system behavior can be unpredictable [130]. For instance, *chaotic nature* of logistics systems was demonstrated in [97] and [145]. Dynamic interactions of decision making among highly autonomous agents was investigated in [45]. The modeled *heterarchical* manufacturing system was able to respond to real-time disturbances caused by rush orders, unexpected machine failures and variable processing times.

Holonic manufacturing systems (HMSs) consist of autonomous, intelligent, flexible, distributed, co-operative agents or holons [112][203][209]. The PROSA reference architecture for HMSs identifies three types of basic holons: resource, product, and order holons. Staff holons are also foreseen to assist the basic holons in performing their work. PROSA augmented with coordination and control mechanisms inspired by natural systems (i.e., food foraging behavior in ant colonies) guarantees that process plans are properly executed under changing conditions, while it continuously forecasts the workload of the manufacturing resources and lead times of the products. The design empowers the product instances to drive their own production; hence coordination can be completely decentralized. In contrast to many decentralized setups, the MES predicts future behavior and proactively takes measures to prevent impending problems from happening [200]. Hence, one of the most promising features of HMSs is that they represent a transition between fully hierarchical and heterarchical systems [18].

Agent-based approaches support the realization of so-called *plug-and-produce* production systems where various elements are joined to a complete production system without manual configuration efforts [56]. The main goal of these developments is the realization of a simply manageable agent platform that provides guidelines and facilitates a fast, platform-neutral implementation of the agent technology.

Learning in control

Dynamic and open real-world environments call for adaptive and *learning systems* equipped with processes that allow them to modify their behavior whenever needed [129]. In [125] centralized and decentralized learning algorithms were introduced. In order to overcome the myopic nature of most agent-based solutions in manufacturing control, a novel holonic MES system architecture was presented in [200] which, while preserving the advantages of heterarchical approaches, predicts the near future. Learning from the past, from the real factory and from the future by means of simulation are considered for *self-learning* and *self-optimizing* assembly systems in [93]. A reference model for decentralized self-adaptive factory control and its application lessons have been reported in [27].

Stochastic dynamic production control by neuro-dynamic programming was proposed in [124]: the developed three-level learning structure scaled up well regarding both the problem sizes and the workload of the production system, and could effectively react to changes and disturbances.

High resolution production management

The practical feasibility of most of the approaches to production modeling and control boils down to providing sufficient information about the involved processes and entities [82]. In order to master the high dynamics in the processes and demand, real-time feedback from production is required [165]. While information flow is easier to manage within and between IT components, it may become critical to maintain links between physical products and related software agents as the products are continually changing and moving without a permanent network connection being guaranteed [119]. Better information flow and transparency can also contribute to further improvement, such as real event-driven control [164], as well as plug-and-produce performance based on autonomous resources and intelligent products [159].

Auto identification (AutoID) techniques, such as radio-frequency identification (RFID) or barcodes as a fallback measure can offer a number of benefits for manufacturing and delivery processes [127]. The basic elements of the *sm@rt logistics* approach are illustrated in Figure 11. Successful tests are reported on the application of an electronic Kanban system with cards equipped with RFID tags [164]. In a similar project [109] a context data model was developed as backbone of the Smart Factory [110].

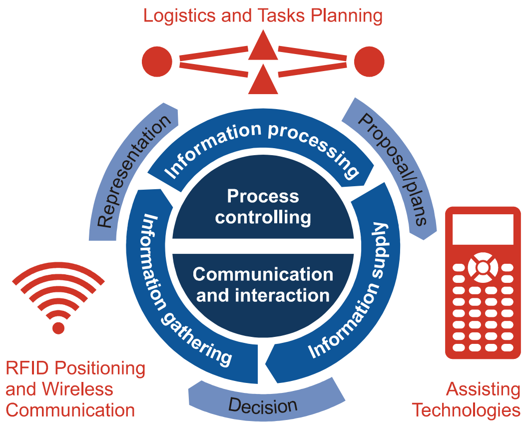

Figure 11. Sm@rt logistics approach (adapted from [164]).

The products themselves can become new elements of control, but this requires a continuous access to their relevant properties and updated state information [226]. This can be achieved by equipping products with RFID transponders, making them thus '*smart products*'. This way product driven (or product-based, or product-oriented) production control can be realized. The final goal is to develop cognitive manufacturing systems where products, processes and resources are endowed with cognitive capabilities [226][227].

The main output of the European research project TraSer was a free, open-source solution platform (in the sense of a development kit and not a centrally maintained entity) for tracking and tracing applications on the item level. The platform provides the background for tracking and tracing in the form of Web services, suits the industrial needs represented, especially those of SMEs. From several ongoing pilot applications involving the TraSer platform, two examples for closed-circuit asset management and supply chains were presented in detail in [127]. Most of the approaches discussed in this subsection are related to the *Internet of Things* (IoT) concepts to be highlighted later in the paper.

6. Related disciplines

6.1. Knowledge management, ontology mapping

In manufacturing organizations, working methods are increasingly influenced by the information and knowledge realm that makes up the counterpart of all manufacturing processes and activities. Regarding the exchange of knowledge that is required to constitute the networks of excellence that underpin both inter-company and intra-company collaboration in projects and day-to-day routine, the importance of adequate *knowledge management* is apparent. Making knowledge transferable is not easy, especially when the transfer of tacit knowledge is concerned [139]. Nevertheless, it is this tacit knowledge that to a large extent determines the effectiveness and efficiency of processes in design, development and production. The ability to share and disseminate knowledge face-to-face, on- and offline, synchronously or asynchronously directly relates to an organization's capacity to interpret information in the appropriate context [16]. Research into knowledge management attempts to integrate the interpretation of information, the related context and processes.

Knowledge management research encompasses the use of representation schemes like taxonomies, topic maps and ontologies to get a grip on the synthesis of the knowledge sources of distinct and multiple stakeholders that are involved. All these stakeholders have different perspectives on the information and knowledge realm, thus rendering an inherent multiple views problem. In this situation, *taxonomies* attempt to pre-structure possible access to the information content [104], whereas *ontologies* ideally allow for a-posteriori determination of meaning and (temporal) hierarchies in this information content [111]. *Topic maps* aim at relating the information content to its ontologies (or typification) [91]. Consequently, the actual denotation of the information content is captured by means of ontologies. The main advantage of using these ontologies is that they aid in understanding the structure of information, which can be used to assess, guide or underpin different situations without having to entirely and repeatedly re-interpret the information content. The inherent danger of interpreting information content in terms of ontologies is that these ontologies will imperceptibly tend to become static descriptions that can be imposed upon other situations. This immediately causes *multiple ontologies* to emerge that will subsequently be maintained independent of the information content. As a result, separate research initiatives attempt to map different ontologies into a bigger scheme of coordinating contexts and perspectives. This *mapping* is also referred to as, for example, ontology alignment, merging, articulation, fusion, integration and morphism.

Current initiatives in the field again focus on the situation where the existing and evolving information content itself triggers the deduction of the temporal formal representation of its denotation. In this, the observation that the actual available knowledge is for the larger part captured in unstructured information (such as text documents, mails, reports, presentations, sketches etc.) leads to the integration of "*structuring unstructured data*" [199] in the overall knowledge and information realm.

From a broader perspective, the upcoming challenge in the field is no longer only to integrate the information content in manufacturing networks, but also to additionally achieve synthesis in the multiple perspectives that exist and different means to capture the denotation of the entities involved.

6.2. Network science

The seminal papers by Barabási and Albert [14][15] laid the foundation of the emerging field of *network science*. The mathematical foundations of graph theory were defined by Erdős and Rényi [51] and resurgence of network science followed Barabási's and Albert's papers. It is increasingly recognized that network science is highly relevant also to engineering as the sheer size of engineered systems poses unique challenges in their design and analysis.

ICT provides rich *connectivity* and thus makes the world highly interconnected. This is an opportunity and also a challenge as the networks tend to be of millions of nodes (e.g., members of social networks, mobile phone owners) and heterogeneous (the nodes include devices and people). Transportation networks have also increased globally, leading to higher connectivity and richer dynamics. Sensor networks have grown at a tremendous pace in the past decade, integrating humans and sensor devices seamlessly. The proliferation of mobile devices is influencing the way society is evolving as a networked one. During the past few years product networks and economic networks have been explored to study the evolution of economics of different countries. The correlation among suppliers, products, and enterprises has been studied in the past five to six years to make the supply chain system more robust [19]. Integrated modeling of all these systems becomes increasingly important. Tools and techniques developed in the past are applicable to networks of tens or hundreds or in extreme cases thousands of nodes. The growth and complexity of the fundamental systems described above necessitate the development of network science principles regarding the representation and analysis of engineered networks.

The structure of networks conveys rich information useful for inference. The past decade has seen a proliferation of *topological metrics*. Here, the important ones are discussed only. The *order* of a network is the total number of nodes (also called vertices), and its *size* is the total number of links (also called edges) in a network. The *degree* of a node is the number of links connecting the node to its neighbors. The *degree distribution* is a two dimensional graph showing the frequency of nodes with different degrees in the network. The network *density* is the ratio between network size m and the maximum possible number of links. One of the most important measures that has been explored is *distance*: the length of the shortest path between two nodes. The *diameter* of the network is the longest distance between any pair of nodes in a network. The *clustering coefficient of a node* measures how other nodes of the network tend to cluster around it. The *clustering coefficient of a network* is the arithmetic mean of the clustering coefficients of all the nodes. The *betweenness centrality* quantifies how much a node is between other pairs of nodes. A measure often used is the ratio between the clustering coefficient and the average path length called *CP ratio*. The *proximity ratio* of a network is the CP ratio between this network and a random network. This property captures the extent of a network's *small-worldness*. The *modularity index* measures the topological similarity in the local patterns of linking [35]. The above measures are appropriate to capture and analyze both the structural properties of large-scale production networks and the network flow of material, information and financial assets [19].

6.3. Game theory

Game theory models and analyses decision making in situations when the outcome depends on the choices of a number of autonomous partners. It is no wonder that game theory is gaining more and more momentum in understanding, designing, and managing the operation of production networks, from dyadic chains up to complex production and logistics networks (for some reviews, see [25][133]). Models of game theory can be broadly classified as cooperative and non-cooperative. The *cooperative* approach assumes that players make agreements and set up coalitions. This approach provides a prediction about the possible outcome of a game without really specifying the actions to be taken. Hence, cooperative models are applicable for designing supply networks. This design may include also agreement upon parameters of a contracting scheme that could be the result of a Nash bargaining game [5][133].

On the operational level, the action-oriented *non-cooperative* models are prevalent that center around determining what the agents should do. Here the players (e.g., enterprises in a supply chain) optimize their own utilities without considering the effect of their decisions on the other parties' utilities. The game is about finding optimal strategies for each player, however, coalitions or federations are not allowed. When decisions are temporally structured (as it is the case with planning problems), the so-called Stackelberg game is usually played where the agents decide sequentially: the leader moves first and the follower responds. There exists a broad literature of dyadic chains where any player could be the Stackelberg leader [25]. If the players posses asymmetric private information, the so-called sequential *principal-agent* model is applied [99]. Finally, repeated games can help one study strategic, long-term customer-supplier relationships.

All in all, collaborations can be modeled by taking a cooperative and next a non-cooperative approach. However, most of the research concentrates only on one of the phases. This is somewhat at odds with a holistic view that was originally expressed by Aumann: "the game is one ideal, and the cooperative and non-cooperative approaches are two shadows" [10]. Recently, for analyzing strategies in a number of business scenarios (such as branding, innovation, re-positioning) the hybrid non-cooperative/cooperative construct of *biform games* has been proposed [20].

6.4. Reverse game engineering or mechanism design

Mechanism design, also considered inverse game theory, has a specific engineering perspective. While it borrows some key concepts of game theory, like strategies, equilibrium and rationality, instead of being interested in the output of a given game, it aims at designing the *rules* of the game that lead to desired social outcomes when agents with private information act following their own utility [117][136]. Mechanism design applies the model of non-cooperative games with players having incomplete information, and investigates how the private information influencing the other players' utilities can be elicited. Accordingly, mechanism design can resolve dilemmas and suboptimal performance in strategic situations by aligning the objectives of the partners. The theory (whose founders were awarded with Nobel Prize in 2007) has already been successfully applied in designing practical auction mechanisms for electronic markets, and analyzing the behavior of automated agents operating on the Internet [134][136]. This success is mainly due to the fact that these environments are *well-structured* as far as distinct regulations and possible actions are concerned. Since this theory considers strategic interactions of self-interested agents with incomplete (private) information, it offers promising applicability also in supply chain research. *Algorithmic mechanism design* [136] pays special attention to the computational aspects of the protocols that are typically ignored by the standard theory, but are essential when implementing multi-agent systems [171].

6.5. Generic mechanisms of cooperation

Evolutionary game theory provides a generic framework for studying and understanding the origin of cooperation in structured populations such as biological organizations, society, or social networks [140]. So as to capture the basic dilemma, namely, that cooperation is always costly because a cooperative agent has cost when helping other(s), the well-known *prisoners' dilemma* (PD) game is applied as the nucleus of models. In an evolutionary setting, this game is played in repeated encounters by agents forming a population that is governed by norms and action rules. However, it is *not* assumed that the agents are rational but only that the successful strategies spread in the population via inheritance, imitation or learning. Even though for the individual, defection is the stable evolutionary strategy, a group, or the population as a whole, would be better off if they rather cooperated. There is a conflict between what is best for the individual and for the community. Hence, staged this way, the PD becomes the core of a public goods game and creates the *social dilemma*.

So far, mathematical analysis, simulation studies and experimentation with human subjects have distinguished five basic mechanisms of cooperation that emerge under the pressure of natural selection (Figure 12) [140]. *Kin selection* operates between genetic and cultural relatives who may act in an unselfish way. *Direct reciprocity* involves that if an agent helps another one, then, in their repeated encounter, it can expect that help will be returned. *Indirect reciprocity* assumes return not from an individual, but a community: if I help you, someone will help me. The base of indirect reciprocity is *reputation*; an individual whose helpfulness is appreciated will more likely get help. Building and maintaining reputation require two basic capabilities: (1) monitoring ongoing interactions in the population, and (2) ensuring public *transparency*. If interaction between individuals is governed by (spatial) locality, *network reciprocity* is at work: cooperators are better off by participating in networks where members help each other. Finally, according to *group selection* competition exists between (and also within) groups.

Indirect reciprocity, since it requires observation, information processing, storage, transfer and strategic thinking, is supposed to have a essential role both in the evolution of human cognitive faculties and the development of social patterns of communication, coordination and cooperation [141]. Indirect reciprocity in public goods games provides opportunity to invent novel cooperation mechanisms for managing production: in a socio-economic environment where commitment to core and protected values of enterprises really matters (see Section 2), reputation will definitely have a strong power for encouraging prudent public behavior [152].

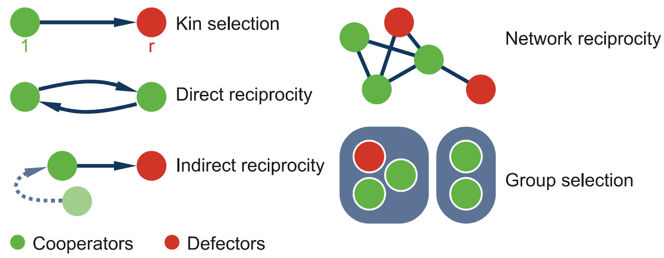

Figure 12. Five mechanisms for cooperation (adapted from [140]).

6.6. Evolutionary approach, evolvable systems in production

The evolutionary approach has provided inspiration for production engineering for a long time. Genetic algorithms, ant colony optimization methods, swarm intelligence and alike—which all borrowed some biological analogy—proved to be applicable in solving engineering optimization problem that were inaccessible to more traditional approaches. However, of particular interest here are models that have a systemic evolutionary view of the interplay of products, processes, resources. This view resulted directly in the concept of biological manufacturing systems [197] and later on, led to the engineering concept of emergent synthesis [195]. It is the basis of evolutionary design, the co-evolution within problem and solution spaces, some recent examples of which are evolutionary product line design [28], and product family grouping [49]. Finally, the SPECIES framework synthesizes the recent academic and industrial developments for modeling and facilitating the coordinated evolution (co-evolution) of products, processes and production systems [187]. The notion of evolution implies responsiveness (so that fitness of entities in an environment could be determined) and, as recent studies of evolutionary biology suggest, beyond natural selection and mutation, some elements of cooperation are also required to construct higher level organizations. Furthermore, the evolutionary views help one study and understand the adaptive evolutionary changes in which exploitation and exploration, persistence and novelty are coupled.

6.7. Complex adaptive systems

The theory of *Complex Adaptive Systems* (CAS) which was put forward by Holland [77] is a new paradigm for studying the structure and dynamics of large systems. Its underlying assumption is that adaptability of systems creates, but at the same time, also resolves complexity. A CAS is in fact a multi-agent system in which "a major part of the environment of any given adaptive agent consists of other adaptive agents, so that a portion of any agent's efforts at adaptation is spent adapting to other adaptive agents" [77]. The central question is realizing an *open* system consisting of autonomous agents that achieves its purpose even under unpredictable conditions, facing a combinatorial explosion of states, non-linear phenomena, uncertain and typically incomplete data and knowledge. For managing such systems, an appropriate *balance* between *control* and *emergence*, *simulation* and *theory* has to be found [175]. Surana et al. propose that various concepts, tools and techniques from the fields of statistical physics, non-linear dynamics and information theory should be used in the study of CAS dedicated to supply networks [175]. A complexity model for networks of collaborative enterprises was given by Csáji and Monostori [34] (see Figure 13).

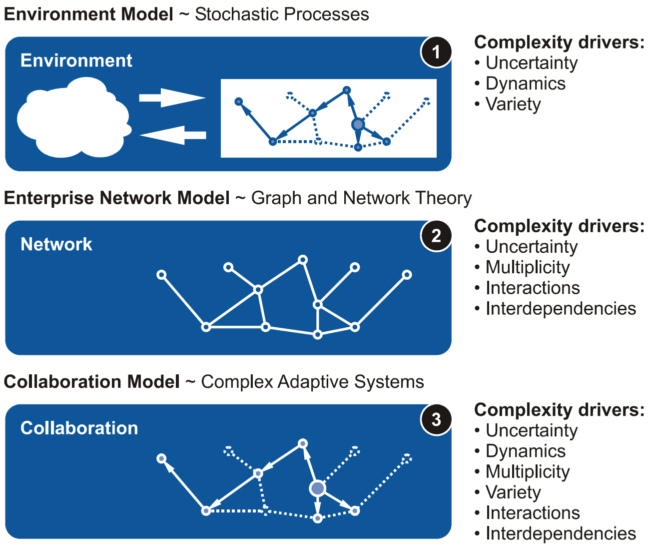

Figure 13. Complexity model for networks of collaborative enterprises [34].

6.8. Control over/of networks

Manufacturing system architectures are evolving from traditional centralized models through distributed models to the recent networked models. Networked manufacturing systems have to be monitored and controlled with the objective of maximizing the Quality of Service (QoS) provided by the manufacturing resources to achieve near-zero down time operations. Monitoring, diagnosing and maintenance are of vital importance in achieving these goals with the help of the advancement of sensor and sensor fusion techniques. Networked sensing and control systems, built on sparse and unreliable networked components, pose research challenges such as *control over networks* and *control of networks*. In the former, primary issues are bandwidth constraints, channel fading and competition for network resources, while in the latter, congestion control, network routing strategies, transmission power management and application level performance, represent key questions [229].

7. Enabling information and communication technologies

7.1. Pervasive, ubiquitous and autonomic computing

Future advances in ICT and especially in sensor and actuator technologies envision a new era of *pervasive, ubiquitous* or *context-aware computing* [57]. When ICT systems are woven into the 'fabric of everyday life', everyone is capable of accessing, exchanging and processing information quickly, efficiently, and effortlessly, without regard to physical location. Pervasive communication systems are expected to transcend the fixed, end-to-end connectivity paradigm and facilitate the spontaneous cooperation of various devices, even without centralized authentication or naming services. Pervasive computing can be realized by novel architectures that are based on the principles of device autonomy, fragmented connectivity, and spatial awareness. As for running production, pervasive computing services provide the backbone of *context-aware applications* [110] in the *smart factory* [109].

Autonomic computing initiated by IBM in 2001 [80] was inspired by the autonomic nervous system of the human body. It focused on the rapidly growing, almost intractable complexity involved in the integration and management of ICT systems. By taking the above analogy, *self-management* of such systems is to be achieved by self-* services like configuration, healing, optimizing and protecting [178]. The *autonomic manufacturing execution system* concept was developed by Valckenaers et al. [201] where the fundamental goal was the cooperation between scheduling and a MES. The autonomic MES uses a given schedule as a guideline for selecting from among task execution alternatives, but it generates solutions which are independent from the externally provided schedule, and in this way maintains the robustness and completeness of the execution.

7.2. Service oriented computing: Grid and Web services

Service-oriented computing (SOC) or *service-oriented architecture* (SOA) constitutes a new computing paradigm. Services offered by Web based software are called *web services*. These services are described by the standardization of WSDL (Web Service Description Language, an XML, i.e., Extensible Markup Language based language). Web services communicate via SOAP (Simple Object Access Protocol) which enables information exchange across platforms in a wide variety of domains. Web services are registered in UDDI (Universal Description, Discovery, and Integration) registry center. Web service integration engine provides the manufacturing industry the ability to horizontally and vertically integrate data across a wide range of machines, plants, vendors and enterprise domains. MES and ERP systems are able to exchange data of distributed processes through the Internet. The overall system comprises of wide-area distributed systems which are typically connected to the Internet or the intranet. By this way, more dynamic and flexible integration of application modules can be achieved [53]. Thanks to the the loose coupling, the application programming interfaces (APIs) of system components can be developed independently. More advanced SOA architectures such as *grid computing* [60] and the *Semantic Web* [74] rely partly also on these properties of Web Services that are expected to play a significant role in developing next generation manufacturing systems [40][53][170]. The development and application of appropriate ontologies is, however, a step which has yet to be taken [222].

By integrating grid and digital manufacturing technologies, Constantinescu and Westkämper introduced the concept of *grid engineering for manufacturing* [31] as a holistic approach and also as a software infrastructure framework appropriate for the rapid prototyping of factories.

7.3. Agent technologies

As previously discussed, agent technologies have gained wide-spread application in all domains of production engineering and management [130]. As for the reasons of why agents provided such a powerful instrument, it was pointed out that this computing paradigm offered inherently novel ways to understand, model, specify, design and manage decentralized and open manufacturing systems. In particular, agents represent a *design metaphor* that enables one to structure domain knowledge (and system design, accordingly) around components that have autonomy and capability to communicate. Agent technology offers a wide array of *software engineering* models, techniques, formal modeling approaches and development methodologies. Finally, agent-based modeling is especially suitable for *simulating* the behavior of complex systems operating in dynamic environments [108].

7.4. Active information carriers, sensor networks

Active information carriers such as RFIDs constitute, beyond doubt, effective automatic identification technology for a large variety of objects that relate in any way to production activities or services [4][154]. As was made clear above, RFIDs are key elements towards increased transparency both within and across organizational borders [22][127]. The reported applications in manufacturing include intelligent product driven supply chain [228], Sm@rt logistics [164], end-of-life management [146], autonomous assembly systems [159], high resolution order management [165], the smart factory [109], product-oriented production control [226], and cognitive production control [227].

Wireless sensor networks (WSNs) provide a vital link between control and controlled systems, i.e., the physical world of production. Recently, a wide variety of inexpensive, low-power wireless microsensors have been embedded in industrial applications where middleware layers connect the sensor and the application layers [83]. In many fields such as quality control, indoor navigation, logistics, warehousing, remote diagnostics, etc., the localization of sensor nodes is crucial. A review of localization algorithms for distributed wireless sensor networks in manufacturing can be found in [61], while [151] discusses maintaining the connectivity of wireless sensor networks using decentralized topology control protocols. Naturally, wireless sensor networks can benefit from the autonomic computing paradigm [116].

7.5. Internet of Things

One of the most exciting paradigms of ICT today is the *Internet of Things* (IoT) [8][24]. From among a number of alternative definitions, one clearly highlights the main difference between IoT and pervasive or ubiquitous computing: "from anytime, anyplace connectivity for anyone, we will now have connectivity to *anything*" [142]. The main enabling factor of IoT is the integration of several technologies, e.g., identification and tracking, wired and wireless sensor and actuator networks, next generation of the Internet, and distributed intelligence for smart objects, to name only the most important ones [8].

As a kind of integration of the information and communication technologies discussed in this section, IoT has unforeseeable application opportunities in manufacturing and will significantly change its present way of functioning. The SmartFactory^{KL} initiative which aims at demonstrating and testing novel factory technologies is on the way towards the *factory of things* [230]. As for the smart product, the closed-loop product lifecycle management (PLM) becomes reality in the era of IoT [92].

8. Towards resolutions of challenges

After having discussed the most compelling challenges for networked manufacturing (Section 4), the paper surveyed the state-of-the-art by taking both a problem and a method oriented view. Now, when it is time to give an overall vision that highlights some promising ideas and research directions, one has to recall that the main requirements were inherently conflicting. Consequently, a safe—sometimes even narrow—path should be found in between two extremes (just like mariners of the antiquity and Ulysses specifically had to find a passage through the rock of Scylla and the maelstrom of Charybdis [79]). These moderated alternatives point towards some essential elements of cooperative and responsive enterprises.Table 1 briefly summarizes the main aspects of the investigations. After characterizing typical solution proposals at two extreme poles, based on conclusions of the state-of-the-art review, it points towards appropriate resolutions. Figure 14 gives a different overview of findings, clustered according to the four relevant domains of production engineering, and classified as strategic, tactical or operational level resolutions. In what follows some important paths toward cooperative and responsive manufacturing enterprises (CoRMEs) are discussed that cut across a number of domains of production engineering and management.

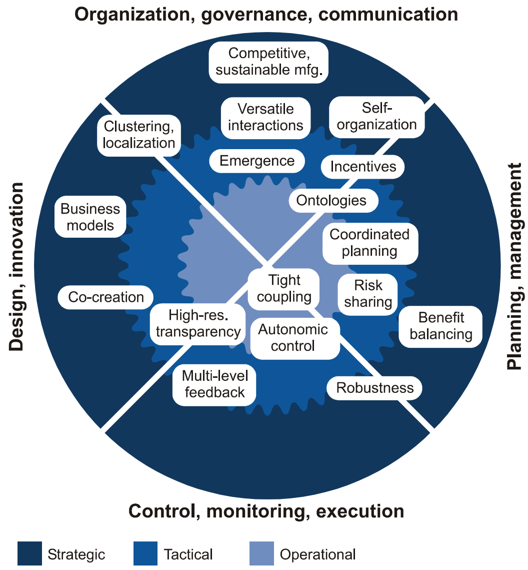

Figure 14. Resolutions pointing towards CoRMEs.

8.1. Towards sustainability based on reputation

As discussed above, sustainable manufacturing exposes a number of social dilemmas [193][196]. These issues can be tackled by the mechanism of *indirect reciprocity* which is based on reputation. For instance, environmental (carbon) footprint, if public, can provide a drive for an improved ecosystem management. In the narrower context of production engineering, Hauschild et al. elaborated a methodology that assesses the environmental impact of production through the entire life-cycle of products [72]. Recently, this method has been transferred to the social domain for assessing social impacts [73]. Kara et al. suggested a model to measure the energy embodied in artifacts as they are produced by global manufacturing supply chains [89]. Schönsleben called for the development of a supplier code of conduct as well as 'green and lean' logistics—both of which require measures that are easy to take and communicate [163]. The Cooperative Effort on Process Emissions in Manufacturing (CO_2PE!) initiative [32] analyses the environmental footprint for a wide range of manufacturing processes with respect to their direct and indirect emissions, which is the first step towards the eco-labeling of machine tools and production systems.

8.2. Cooperation based on trust and reputation

In the context of CoRMEs, the generic mechanisms of cooperation are relevant in a number of ways. First, on global markets, traditional, long-lasting relationships are more and more frequently replaced by one-short interactions. Transactions that are typical in e-business [179] or even co-design [191] are inherently based on indirect reciprocity that can be built on reputation only. Fortunately, the same ICT technologies which provide a vehicle for such interactions through universal connectivity and omnipresent computation (see Section 7) can also be applied to performance monitoring and information

Table 1 Challenges and resolutions pointing towards cooperative responsive manufacturing enterprises.

Aspects	***Characteristics***		***Resolutions***
Design, innovation			
Demand complexity	Exogenous, complex demand	Full customer involvement	Co-creation
Variability	Standardized, modularized offer	Customized, personalized production	Product clustering and localization
Innovation management	Over- and/or conflicting regulation	Developing and maintaining trust	Innovative business models
Organization, governance, communication			
Drivers	Preference to created values	Preference to core and protected values	Competitive and sustainable
Interaction mechanism	Transactional	Relational, informal	Versatile
Network organization	Central, optimal	Eventual, open and multiplex	Autonomic, self*
Global behavior	Controllable	Emergent	Emergent with guaranteed properties
Information sharing	Truthful, symmetric	Asymmetric	Incentive to share information truthfully
Knowledge sharing	Common ontology based	Local ontology based	Mapped/merged ontologies
Decision making, planning and management			
Attitude	Autonomous, rational	Cooperative	Incentive for cooperation
Behavior	Opportunistic	Benevolent	Risk sharing, benefit balancing, trust building
Coordination	Upstream, hierarchical	Centralized	Coordinated planning
Timeliness	Hierarchical, fixed time planes	Reactive in real-time	Reactive on appropriate time plane
Local planning	Foresight, optimization	Reactivity	Responsiveness, robustness
Performance evaluation	Forced compliance	Opportunism, free riding	Measurable, (partially) public
Control, execution, monitoring and feedback			
Control structure	Hierarchical	Heterarchical	Holonic, autonomic
Sensing	Fixed sensors	Auto identification	Wireless sensor networks
Information gathering	Hierarchy level oriented	Plethora of information	Aggregation, appropriate time planes, data mining
Transparency of information	Limited	Complete	High resolution
Feedback dynamics	Lazy and delayed feedback	No isolation of decision levels, increased complexity	Multi-level multi-loop feedback
Simulation	Off-line, reactive	Proactive	Tight coupling of the digital and real world

sharing that are prerequisites both for building and keeping track the reputation of individual partners. The possibilities of establishing federations, coalitions, but also of manipulating and exploiting them in some opportunistic way are unlimited. Appropriate forms of lateral collaboration between suppliers, such as supplier parks organized with cooperative clusters [173] can be formed by leveraging *network reciprocity* and *group selection*.

8.3. The service aspect

As it was shown, *service* permeates manufacturing in a number of ways. Taking a more generic stance, one can regard service as the application of competences by someone to the benefit of another one [205]. Service essentially implies cooperation; its basic question is 'How can I help you?' Service provides a novel view for understanding and interpreting economic phenomena behind all production, by implying that value is created collaboratively, during an interaction of mutual exchange [193][196]. In the broadest context, ecosystems can be modeled as service providers for a number of human activities including manufacturing [144]. When managing supply chains under volatile market conditions, supply can be considered a service that provides not only goods with guaranteed service level but also flexibility to another partner. Pricing this service depends not only on the goods produced and delivery performance, but also on the reliability of forecasted demand communicated [208]. Collaboration using novel ICT also opens avenues for *e-maintenance*, a new kind of maintenance service of manufacturing systems [132].

Finally, service makes sense from the very concept of products. Recall that in fact the *flow of products* is what physically connects the enterprises. Recent advances in information technology make it possible to equip products throughout their whole life-cycle with digital assistants. Given this opportunity, products could get a central role and handle their own interests and requirements which are met by services of manufacturing resources [119][203]. Most importantly, *intelligent products* mirror the way in which enterprises cooperate physically. They coordinate along their manufacturing trajectory regardless whether there is a formal organization that governs the enterprises involved. Managing the real-time cooperation amongst enterprises through intelligent products may benefit from the fact that the corresponding flow of products exists in a coherent and consistent reality. However, taking this radical turn, one is confronted with the issues of what would keep the services together, how to account for the multiplication of decisions, as well as how to make strategic decisions and perform tactical level advance planning at all.

8.4. Interactive computing

One cannot doubt that the concept and technology of agents take an eminent role in realizing CoRMEs. By the application of available technology, agents can sense the physical world via a huge variety of sensors and control it via a multitude of actuators. They can cope with highly dynamic environments and changing resources, and will also be able to evolve towards a more implicit and proactive interaction with humans [130]. However, in the background a more generic issue is rarely touched upon: could agents in principle extend the limits of computation and computability? For quite a long time, the question if interaction could provide a more powerful paradigm for computation than the traditional algorithmic models has been posed [214]. Agent technology provides an excellent basis for realizing mixed-initiative problem solving that supports an ongoing, dynamic interleaving of contributions from human users and computational agents. This is a collaborative activity aimed at converging to some solution where goals and commitments may come from either party. This way of problem solving relies heavily on interaction; in fact, it is close to how engineers—even in possession of deficient knowledge—get to the bottom of problems [68]. However, this interpretation raises novel issues regarding the role of engineers, their way of thinking and problem solving as well as responsibilities.

9. Industrial case studies

The industrial case studies discussed in this section illustrate the implementation of some of the essential elements of CoRMEs. These solutions are in line with those summarized in Table 1, and the case studies demonstrate that the paths between the extremes of the table can be found. They also underline that the thinking towards CoRMEs is not limited only to traditional discrete manufacturing.

9.1. 3DWorknet: machining service network

In the current manufacturing industry, the entire process chain from engineering to expedition is quite inefficient. The process chain contains many different departments that generally communicate with each other through conventional 'paper' means and meetings. Another drawback is that several islands of optimization are created, which over the entire process chain results in a lower efficiency. 3DWorknet (currently under development at the University of Twente) aims at shortening the logistics tasks prior to fabrication, through a high degree of digitalization, integration, automation and standardization [183][184]. Additionally, it focuses on fabrication in standardized production plants—also called 'McMill' for milling environments and 'McRapid' for rapid manufacturing application—connected to the 3DWorknet network. To vouch for the quality of the system, processes and products, a quality management system (QMS, conform EN9100) is being developed in close conjunction with the workflow management system. The approach is based on achieving adequate integration between product quality, process quality, effective and efficient workflow management, as well as transparent and structured order processing.

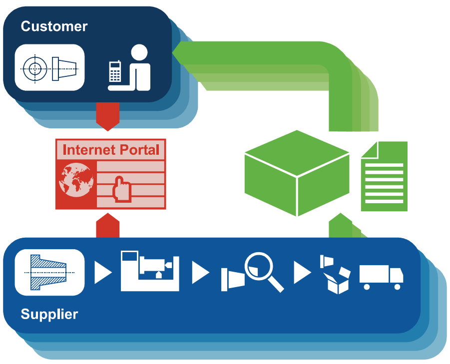

Figure 15. CNC Worknet workflow in comparison to the conventional one.

The system will function around an Internet portal (Figure 15). Process plans and quotations are generated (semi-) automatically from the technical product data provided. After customer assent, the prices, transportation costs and delivery times determine the choice of the standardized production plants (McMill or McRapid). The architecture connects all the different applications of 3DWorknet to one information management kernel. Any application based on this architecture focuses on its main tasks within the network of co-operating production plants. Within the architecture of 3DWorknet, seven application areas are discerned. Each of them governs part of the logistics and organizational processing in the Internet portal and in the 3DWorknet fabrication network.

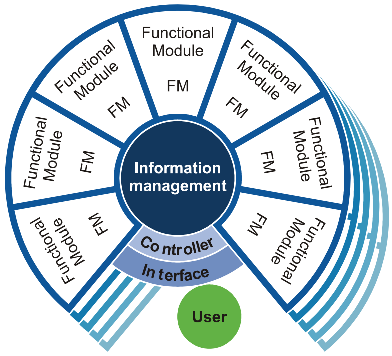

Figure 16. 3DWorknet architecture.

The most important achievement of the system is that the Quality Management System and the Workflow Management have been fully integrated in the activities of the company. Together, they prove their applicability by showing high flexibility in the processing of hundreds of orders per day, over different production locations, realizing coordinated and robust planning, information sharing, decision making as well as risk and benefit sharing. As an example, the McRapids are available via the Shapeways portal [168] where customers have either the opportunity to order existing 3D models from a library, or upload their own models to be printed.

9.2. Customize-to-order production in dynamic supply loops

Demand in the automotive industry is characterized by low and fluctuating quantities for a growing variety of customized products. As a response, the European project AC/DC defined a vision to provide a vehicle production and supply system capable of delivering customized vehicles within five days [52][122][172]. This vision required a radical reduction of the supply network lead time and also the definite increase of responsiveness and planning flexibility in the overall automotive production network. Hence, AC/DC developed an approach called *customize-to-order* (CtO) which combines the advantages of the traditional build-to-order (BtO) and build-to-forecast (BtF) methods. While in the case of BtO, the production of parts or components is triggered and 'pulled' by orders, in CtO customer-anonymous components are prefabricated according to forecasts and then customized either by software and/or by parameterization at a late stage of production. Accordingly, one of the main research tracks of the project was to *design* and develop automotive components whose variety can be realized this way (e.g., smart actuators, modular sensors or an active rear axle) [52].

The other main research track was aimed at developing new supply planning methods that can exploit the characteristics of CtO components: their smaller physical variety, more precise forecasts and risk pooling potential [174]. The *Dynamic Supply Loops* (DSL) planning method coordinates local planning decisions and provides means for turning the cooperative attitude of partners into a competitive advantage [52]. The core concept is a flexible readjustment of the supply network structure and decisions based on collaborative planning processes in closed, one-stage feedback loops between tier$_n$ and tier$_{n+1}$ both on the strategic and the tactical planning levels. On the operational level where responsiveness to disturbances is of primary importance, DSL controls event handling processes.

On the tactical level, the DSL changes the practice of upstream planning by involving the supplier into the decision making: mid-term demand and supply plan scenarios are exchanged, as shown in Figure 17. Principles for *benefit balancing* have been developed to provide partners an incentive to act in a cooperative way. Hence, the $tier_{n+1}$ supplier offers price discounts for its preferred plans [48]. This can be interpreted as a combination of the menu of contracts and the price discrimination approaches of the classical microeconomic theory [117]. DSL is a viable compromise for more optimized inter-company planning: it offers a platform for other partners' options, while keeping communication and decision complexity at bay through a relatively simple information exchange and decision protocol confined to immediate partners in a chain. DSL is open to embed standard planning techniques available in ERP systems and novel incentive schemes alike. According to simulation results on a multi-echelon model, DSL outperforms traditional upstream planning and facilitates channel coordination [48]. Although it has been developed to support collaboration in an automotive supply chain, DSL has no special assumptions that would hinder its transfer to other industrial sectors.

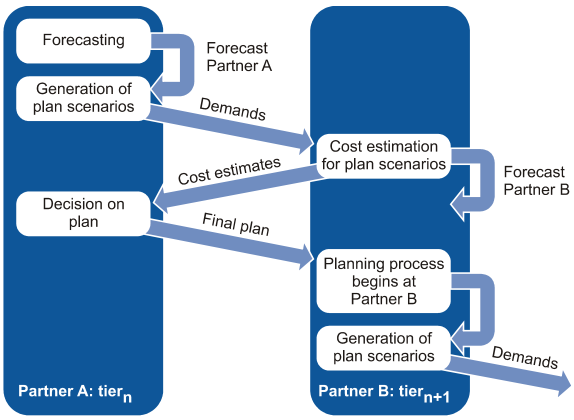

Figure 17. Tactical planning protocol of the Dynamic Supply Loops [52].

The vision of AC/DC became especially relevant at the time of the financial downturn of late 2008 that had serious impacts on the automotive industry. At that time, dramatically decreased market demand caused heavy fluctuations in sales and increased cost and service level pressure both on OEMs and suppliers. According to earlier practice, component supply as well as production systems and supply chains were optimized for operation at maximum utilization rate without explicitly supporting flexibility. Lack of flexibility and reactivity, as well as restricted communication and collaboration between the partners led to severe planning inconsistencies, such as material shortages that propagated along the chains and ramified to production line shutdowns, too. However, the fast transition of the project's result into the practice made the supply network as a whole more flexible, less vulnerable and more efficient. By the end of the project, at a reduction of inventory levels down to 50%, lead time of products was shortened by up to 85%, while keeping a ±25% daily capacity flexibility of production resources.

9.3. *Mass production of customized consumer goods*

The particular background to this study was a national academia-industry research and development project aimed at improving the performance of a network that produces *customized mass products* [128][206]. The network was woven around a focal manufacturer by suppliers of components and packaging materials. The manufacturer—one of the largest of its kind in the world—produced on the average several million units per week from a mix of thousands of low-tech electronics products. Some of the products were sold by retailers under their own labels and this made the market situation extremely uncertain and complex. Against all these uncertainties, exploiting economies of scale of mass production technology was a must. The main goal of the project was to plan and control the behavior of this network on different aggregation levels and time horizons, but on each horizon in a responsive manner. Since the focal manufacturer gave the heartbeat to the network, special emphasis was put on scheduling and controlling its operations. The key to coordinated planning was to master essential conflict situations time and again, in a robust and reliable way.

The solution to the above network coordination problem was based on three kinds of developments:

- Processes and establishment of a media for sharing information about the actual and expected situations, demand and supply, as well as of the future intentions (i.e., plans) of autonomous network partners [207].
- Efficient local scheduling, even with rich, large-scale problem instances [43]. This is a key also to predictable behavior.
- Monitoring the execution of schedules in a real-time manner, anticipating future disturbances and critical situation on the shop floor via simulations and adapting schedules to changing conditions, with minimal ramification of changes [126].

The operation of the factory is determined by production scheduling that takes all the known temporal, resource, material availability and technological constraints into account. Real-time production monitoring and control ensure the execution of the schedule, while component supply guarantees the availability of necessary materials and components. All the above system elements have been installed and deployed at the focal manufacturer. A coordination platform realized as a Web application supports the exchange and mapping of demand and supply related information both on the tactical and operational levels planning [207]. Finally, so as to make partners interested in cooperation and truthful information exchange, an incentive scheme was developed that facilitates the sharing of risks and benefits when acting together in supply planning [208]. The crux of the coordination problems exposed here involve decentralized decision making with asymmetric information, hence they call for the use of the theory of mechanism design.

9.4. *High-mix low-volume production systems*

With the growing attention to produce to requirements that become more and more diverse, the need for cooperative and responsive enterprises has risen substantially in recent years. One of such phenomena is the increasing use of *high-mix, low-volume* (HMLV) production systems. Here, an industrial case is reported to illustrate the scenario where the CoRMEs fit into this type of complex decision making. Specifically, it deals with the issue of allocating inventory at different stages of production to different locations. The products have a large variety but high degree of component commonality. The finished goods (FG) are sold in different countries world-wide, though with mark up and margins that differ widely. Careful consideration is necessary in order to avoid committing common components too early, and losing the flexibility to potential future orders which may have higher revenue opportunities. Although the global supply chain network may appear to be complex, the procurement and assembly lead times are relatively short. Thus, the requirements for cooperation and responsiveness are essential for the business success: decisions regarding when to deploy which raw material (RM) for which FG in order to maximize revenue have been confronting the management for years.

In the project, stock keeping units (SKUs) of RM are considered as the *collaborating agents* that strive to maximize their contribution to the revenue of the company. With component commonality, a particular RM item can be employed in different variants of FG and generate different amount of revenues. The criticality of an RM item for each FG is represented by its internal marginal revenue. The internal marginal revenue for an RM item includes bill of material (BOM) information, a number of cost and profit factors, and risks associated with it. The major risk factors are supply risk (procurement lead time, supplier quality) and demand risk (demand, usage, commonality, obsolescence).

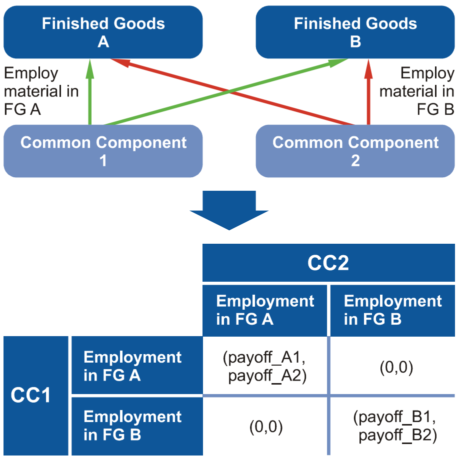

Figure 18. Game theory setting for raw material allocation.

The coordination of RM can then be performed in a *game theory* setting (Figure 18). The set of players are the common components. The strategies for each player are employment in either one of the FGs given the employment of other players. The payoffs for each player are determined by their criticality depending on the share of FG revenue minus the lost revenue opportunities of unemployed unique components.

Given a stream of customer orders (COs) for different FGs, the players decide whether to get employed in the FG of the current CO or not. In this model, it is assumed that each CO is of one unit FG. The decision to respond immediately, postpone the response (backorder) or deny the response (lost sale) is based on the immediate cost and profit of employment and the potential additional cost for backorder/loss of sale. In order to satisfy a CO, some common component RMs will lose the flexibility to serve other future orders. This can be included in the payoff function by estimating the distribution of product variants in the future CO stream and balancing it with the replenishment characteristics of the RM items.

9.5. Coordination for construction of high-rise customized residential housing

Residential housing reflects the living styles, preferences, status, and economics of people who live there. Naturally, it is a fertile ground for *customization*. In particular, with relative poor advancement in productivity improvement in construction industry, there has been substantial interest in enhancing collaboration and responsiveness in an industry known to be fragmented with multiple levels of contracting

Customers' needs are wide-spread and difficult to ascertain. Customized housing enables end customers to give input to the requirements at different stages of production. While customer orders can be placed any time, the specifications from different customers can be equally difficult to predict. Once an order is placed, the variety of different construction materials need to be ordered. Though, deliveries may have different lead times, and, like in manufacturing resource planning, the time required for the particular job could also be difficult to ascertain. Moreover, the processing time for a single job varies as attributes of the specification differ. The traditional critical path based planning method failed to capture the temporal dynamics and resulted in a frequent change of schedule on the construction site. Hence, albeit conceptually attractive, customized housing has not been widely adapted.

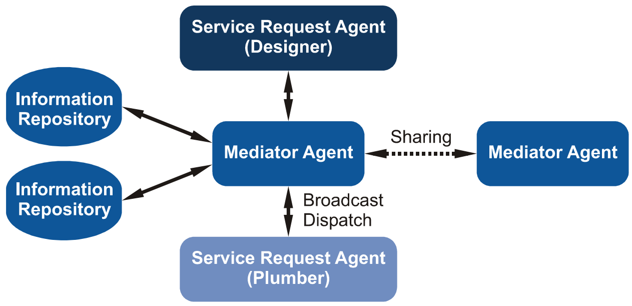

Figure 19. Mediated agent coordination framework.

Given the distributed nature and complexity of the problem, and considering the requirements for close collaboration and responsiveness, a *mediated agent coordination* framework has been proposed to utilize information technology so as to bridge the coordination gaps in housing construction. The coordination framework considers every labor or resource consumption as *services*. It is composed of the following types of agents (Figure 19):

- *Service Request Agent* (SRA): Sends requests to mediator agents with specification on the requirements of the job;
- *Service Provider Agent* (SPA): Represents workers with different skill levels and preference on job;
- *Mediator Agent* (MA): Responsible for dispatching jobs to agents according to different criteria (location, contractors);
- *Information Repository* (IR): Database that stores coordination related information of agents, including current status of SPAs, attributes of SRA and SPA.

The idea of introducing a MA is from ubiquitous computing where distributed device and dynamic service requests are coordinated to satisfy customers' needs based on location information. It is the IR that stores and updates useful coordination information for MA. To start a new coordination process the mediator gets a request from SRA (i.e., website for customers). It queries IR for capable SPAs and broadcasts service requests associated with costs. MA starts to bind the requested service to providers after it receives utility specifications, which is unknown to other agents, from the SPAs. MA optimizes the utility for all the requested services. If no reply is received from SPA, the mediator will broadcast to other mediators to dispatch the service. It is expected that the mediator is able to respond to the dynamics of the system by keeping track of the SPAs, while processing information from other conflicting parties.

9.6. Networked manufacturing control

The EU project MABE and follow-up research applied *holonic MES* technology (HMES) to a networked production system [200]. MABE focused on a virtual enterprise consisting of nine SME-sized companies where the number of companies is likely to vary and grow over time. The main objective was the optimized utilization of the physical resources as well as information. The nodes in the network of production systems are factories performing heat treatment of metallic materials. Figure 20 (lower part) shows the temperature profile and processing steps of the case hardening process.

The HMES facilitates resource sharing on the level of the entire network and provides access to and usage of all relevant information throughout this network. From the HMES perspective, this network presents itself as a production system with at least two levels of organization: the network level and the factory level. Inside factories, multiple levels (areas, departments, workstations) typically exist. In principle, the HMES based on PROSA [203] is a *fractal design* mirroring the organization of the underlying production system(s).

The PROSA architecture turned out to be highly suited for this challenge. The *product holons* provide the facility to check for compatible trajectories whereas the *order holons* use a delegate MAS [78] to discover batching opportunities within the short-term forecasts or, alternatively, to trigger the build-up of such batches. Moreover, an accurate model of a multi-chamber oven was developed. This development demonstrated how the HMES was able to cope with complex part flows through production equipment. The experience revealed that the implementation efforts mostly consist of creating executable models of the equipment and processes [210].

The HMES equally scales in the other direction to the network level. In a network of factories, the transport operations with trucks, the storage at different sites, and the production processes offered by factories are all indistinguishable from similar operations on lower levels within single factories. The HMES is a fractal design, which repeats itself on the various levels of the underlying (networked) production system. The mechanisms that cope with the presence of departments within a factory also cope with factories in a network of factories. In fact, the higher levels in the network are easy because products and parts are storable and transportable in between processing steps.

Most importantly, the presence of both resource and order holons is crucial. Alternative approaches which, for instance, only comprise intelligent resources intrinsically struggle to deliver such adaptability and scalability [172]. The HMES design resembles the organization in which premium-paying customers have a 'butler' who manages their 'production orders' on their behalf. In contrast, current production systems—aimed at mass-customization—only cope with situations for which the 'script' was known at their design time. When a new product model is introduced, the production lines need upgrading and the human workers receive training.

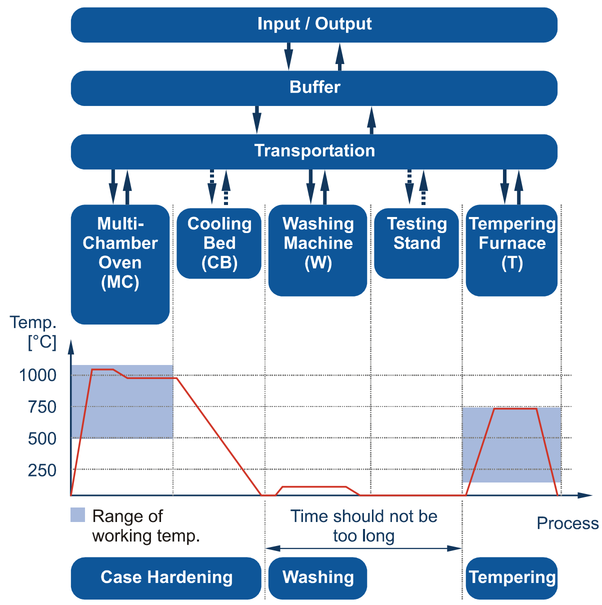

Figure 20. Heat treatment: Processing steps with temperature profile.

Importantly, in the latter case, the adaptation needs to be orchestrated. The HMES avoids the above scaling issues. As production networks lack a single command and control center, the research on a networked HMES addressed challenges originating from semi-open organizations. First of all, the HMES supports non-disclosure by creating holons to act on behalf of other ones, while exchanging information on a need-to-know basis. Research on trust in semi-open organizations resulted in a decision support framework based on track records of the holons (resources, orders) in their interactions [155].

10. Concluding remarks

Manufacturing cannot be considered in isolation any longer: enterprises have to operate in dense interaction networks both with their kin and their socio-ecological environment. At the same time, enterprises have to continuously consider the split between reality and their reflection on what is going on in the world. In other words, enterprises have to rely on a model of their reality, whilst simultaneously and unremittingly adjusting that model itself. As the paper discussed, the key challenges are heavy, because they directly stemming from generic conflicts between competition and cooperation, local autonomy and global behavior, design and emergence, planning and reactivity, as well as uncertainty and abundance of information. Based on the survey of various solution proposals, one can conclude that balanced resolutions invariably point towards cooperation and/or responsiveness. It was emphasized—and also illustrated through a series of industrial case studies—that production engineering research has to integrate results of related disciplines as well as a broad range of contemporary information and communication technologies. Conjointly, this enables the adequate facilitation of cooperation and responsiveness that are vital in competitive and sustainable manufacturing.

Acknowledgements

The authors wish to thank all the contributors for having sent material and/or helping improve earlier versions of the paper: R. Akkerman, J. Aurich, E. Carpanzano, G.

Chryssolouris, C. Constantinescu, B. Denkena, P. Egri, F. Erdélyi, B. Iung, T. Kaihara, Zs. Kemény, D. Mourtzis, S. Newman, P. Nyhuis, A. Radke, B. Scholz-Reiter, P. Schönsleben, A. Valente, T. Vámos, C. Wang, Y. Wang, E. Westkämper, J. Yan. The Hungarian authors acknowledge the support of the Hungarian Scientific Research Fund (OTKA) through grant T-73376 "Production structures as complex adaptive systems", and of the National Office for Research and Technology, Hungary (NKTH) through grant "Digital, real-time enterprises and networks" OMFB-01638/2009.

References

[1] Abele, E., Kluge, J., Näher, U., 2006, *Handbuch Globale Produktion*, Hanser, München, p. 170.

[2] Albrecht, M., 2010, *Supply Chain Coordination Mechanisms*, Springer.

[3] Akkerman, R., van der Meer, D., van Donk, D.P., 2010, Make to Stock and Mix to Order: Choosing Intermediate Products in the Food-Processing Industry, *Int. J. of Production Research*, 48/10-12:3475–3492.

[4] Amaral, L.A., Hessel, F.P., Bezerra, E.A., Correa, J.C., Longhi, O.B., 2011, eCloudRFID – A Mobile Software Framework Architecture for Pervasive RFID-based Applications, *J. of Network and Computer Applications*, 34/3:972–979.

[5] Argoneto, P., Bruccoleri, M., Lo Nigro, G., Perrone, G., Noto La Diega, S., Renna, P., Sudhoff, W., 2006, High Level Planning of Reconfigurable Enterprises: a Game Theoretic Approach, *CIRP Annals - Manuf. Tech.*, 55/1:509–512.

[6] Arrow, K.J., 2000, Innovation in Large and Small Firms. In: Swedberg, R., *Entrepreneurship: the Social Science View*, Oxford University Press, pp. 229–243.

[7] Arshinder, Kanda A., Deshmukh, S.G., 2008, Supply Chain Coordination: Perspectives, Empirical Studies and Research Directions, *Int. J. of Production Economics*, 115:316–335.

[8] Atzori, L., Iera, A., Morabito, G., 2010, The Internet of Things: A Survey, *Computer Networks*, 54:2787–2805.

[9] Auerswald, P., Branscomb, L.M., 2008, Research and Innovation in a Networked World, *Technology in Society*, 30/3-4:339–347.

[10] Aumann, R.J., 1959, Acceptable Points in General Cooperative n-Person Games, In: *Contribution to the Theory of Games IV*. Princeton University Press, pp. 287–324.

[11] Aurich, J.C., Mannweiler, C., Schweitzer, E., 2010, How to Design and Offer Services Successfully, *CIRP J. of Manufacturing Science and Technology*, 2/3:136–143.

[12] Axelrod, R., 2006, *The Evolution of Cooperation*, (revised ed.), Perseus Books Group.

[13] Balakrishanan, A., Kumara, S.R., Sundaresan, S., 1999, Manufacturing in the Digital Age: Exploiting Information Technology for Product Realization, *Information Systems Frontiers*, 1/1:25–50.

[14] Barabási, A.-L., Albert, R., 1999, Emergence of Scaling in Random Networks, *Science*, 286:509–512.

[15] Barabási, A.-L., Albert, R., Jeong, H., 2000, Scale-Free Characteristics of Random Networks: The Topology of the World Wide Web, *Physica A*, 281:69–77.

[16] Bernard, A., Tichkiewitch, S. (eds.), 2008, *Methods and Tools for Effective Knowledge Life-Cycle Management*, Springer.

[17] Blackhurst, J., Wu, T., O'Grady, P., 2005, PCDM: A Decision Support Modeling Methodology for Supply Chain, Product and Process Design Decisions, *J. of Operations Management*, 23/3-4: 325–343.

[18] Bongaerts, L., Monostori, L., McFarlane, D., Kádár, B., 2000, Hierarchy in Distributed Shop Floor Control, *Computers in Industry*, 43/2:23–137.

[19] Borgatti, S.P., Li, X., 2009, On Network Analysis in a Supply Chain Context, *Supply Chain Management*, 45/2:5–22.

[20] Brandenburger, A., Stuart, H., 2007, Biform Games, *Management Science*, 53:537–549.

[21] Bretzke, W.-R., 2009, Supply Chain Management: Notes on the Capability and the Limitations of a Modern Logistic Paradigm, *Logistics Research*, 1/2:71–82.

[22] Brown, D.E., 2006, *RFID Implementation*, McGraw-Hill Professional.

[23] Bruccoleri, M., Lo Nigro, G., Perrone, G., Renna, P., Noto La Diega, S. 2005, Production Planning in Reconfigurable Enterprises and Reconfigurable Production Systems, *CIRP Annals - Manuf. Tech.*, 54/1:433–436.

[24] Bullinger, H.-J., ten Hompel, M., 2007, *Internet der Dinge*, Springer.

[25] Cachon, G., Netessine, S., 2004, Game Theory in Supply Chain Analysis, In: Simchi-Levi, D., Wu, S.D., Shen, Z.-J. (eds.), *Handbook of Quantitative Supply Chain Analysis: Modeling in the eBusiness Era*, Kluwer.

[26] Cachon, G.P., 2003, Supply Chain Coordination with Contracts, In: [37], pp. 229–339.

[27] Carpanzano, E., Jovane, F., 2007, Advanced Automation Solutions for Future Adaptive Factories, *CIRP Annals - Manuf. Tech.*, 56/1:435–438.

[28] Chen, S.L., Jiao, R.J., Tseng, M.M., 2009, Evolutionary Product Line Design Balancing Customer Needs and Product Commonality, *CIRP Annals - Manuf. Tech.*, 58/1:123–126.

[29] Chikán, A., 2007, The New Role of Inventories in Business: Real World Changes and Research Consequences, *Int. J. of Production Economics*, 108:54–62.

[30] Chryssolouris, G., Makris, S., Xanthakis, V., Mourtzis, D., 2004, Towards the Internet Based Supply Chain Management for the Shiprepair Industry, *Int. J. of Computer Integrated Manufacturing*, 17/1:45–57.

[31] Constantinescu, C., Westkämper, E., 2008, Grid Engineering for Networked and Multi-Scale Manufacturing, *Proc. of the 41st CIRP Int. Conf. on Manufacturing Systems*, May 26-28, 2008, Tokyo, Japan, pp. 111–114.

[32] CO2PE! (Cooperative Effort on Process Emissions in Manufacturing) http://www.mech.kuleuven.be/co2pe!, accessed at 2011.01.05.

[33] Corvello, V., Migliarese, P., 2007, Virtual Forms for the Organization of Production: A Comparative Analysis, *Int. J. Production Economics*, 110:5–15.

[34] Csáji, B.Cs., Monostori, L., 2008, A Complexity Model for Networks of Collaborating Enterprises, *Proc. of the 17th IFAC World Congress*, July 6-11, Seoul, Korea, pp. 13833–13838.

[35] Cui, L., Kumara, S.R., Albert, R., 2010, Complex Networks: An Engineering View, *IEEE Circuits & Systems Magazine*, 10/3:10–25.

[36] Daily, G.C., et al. 2000, The Value of Nature and the Nature of Value, *Science*, 289/5478:395–396.

[37] de Kok, A.G., Graves, S.C., (eds.), 2003, *Supply Chain Management: Design, Coordination, Cooperation. Handbooks in OR and MS*, Vol. 11, Elsevier.

[38] Denkena, B., Lenz, A.T., Lorenzen, L.-E., 2009, Agile Planning for Gentelligent® Production. *Proc. of the 3rd Int. Conf. on Changeable, Agile, Reconfigurable and Virtual Production CARV-09*, Munich, Germany, pp. 79–88.

[39] Dietz, J.L.G., 2006, *Enterprise Ontology: Theory and Methodology*, Springer.

[40] Dong, B., Qi, G., Gu, X., Wei, X., 2008, Web Service-Oriented Manufacturing Resource Applications for Networked Product Development, *Advanced Engineering Informatics*, 22:282–295.

[41] Donner, R., Scholz-Reiter, B., Hinrichs, U., 2008, Nonlinear Characterization of the Performance of Production and Logistics Networks, *J. of Manufacturing Systems*, 27:84–99.

[42] Dowlatshahi, S., Cao, Q., 2006, The Relationships Among Virtual Enterprise, Information Technology, and Business Performance in Agile Manufacturing: An Industry Perspective, *European J. of Operational Research*, 174/2:835–860.

[43] Drótos, M., Erdős, G., Kis, T., 2009, Computing Lower and Upper

Bounds for a Large-Scale Industrial Job Shop Scheduling Problem, *European J. of Operational Research*, 197/1:296–306.

[44] Dudek, G., Stadtler, H., 2005, Negotiation-based Collaborative Planning between Supply Chain Partners, *European J. of Operational Research*, 163:668–687.

[45] Duffie, N.A., Prabhu, V.V., Kaltjob, P.O., 2002, Closed-loop Real-time Cooperative Decision-making Dynamics in Heterarchical Manufacturing Systems, *J. of Manufacturing Systems*, 21/6:409–418.

[46] Duffie, N.A., Roy, D., Shi, L., 2008, Dynamic Modeling of Production Networks of Autonomous Work Systems with Local Capacity Control, *CIRP Annals - Manuf. Tech.*, 57/1:463–466.

[47] Duffie, N.A., Shi, L., 2009, Maintaining Constant WIP-regulation Dynamics in Production Networks with Autonomous Work Systems, *CIRP Annals - Manuf. Tech.*, 58/1:399–402.

[48] Egri, P., Döring, A., Timm, T., Váncza, J., 2011, Collaborative planning with benefit balancing in Dynamic Supply Loops, *CIRP J. of Manufacturing Science and Technology*, in print.

[49] ElMaraghy, H.A., AlGeddawy, T., Azab, A., 2008, Modelling Evolution in Manufacturing: A Biological Analogy, *CIRP Annals - Manuf. Tech.*, 57/1:467–472.

[50] ElMaraghy, H.A., ElMekkawy, T.Y., 2002, Deadlock-free Rescheduling in Flexible Manufacturing Systems. *CIRP Annals - Manuf. Tech.*, 51/1:371–374.

[51] Erdős, P., Rényi, A., 1959, On Random Graphs - I, *Publicationes Mathematicae*, 6:290–297.

[52] Ericsson, R., Becker, R., Döring, A., Eckstein, H., Kopp, Th., Poslu, I., Váncza, J., (eds.), 2010, *From Build-to-Order to Customize-to-Order: Advancing the Automotive Industry by Collaboration and Modularity*, The AC/DC Consortium, ISBN 978-91-633-6973-5.

[53] Estrem, A.E., 2003, An Evaluation Framework for Deploying Web Services in the Next Generation Manufacturing Enterprise, *Robotics and Computer Integrated Manufacturing*, 19:509–519.

[54] Ewersheim, W., Bochtler, W., Grabler, R., Kolscheid, W., 1997, Simultaneous Engineering Approach to an Integrated Design and Process Planning, *European J. of Operational Research* 100/2:327–337.

[55] Fathianathan, M., Panchal, J.H., Nee, A.Y.C., 2009, A Platform for Facilitating Mass Collaborative Product Realization, *CIRP Annals - Manuf. Tech.*, 58/1:127–130.

[56] Feldmann, K., Wolf, W., Weber, M., 2007, Design of a Formal Model for the Specification of Agent Platforms Based on Plug&Produce-able Production System, *Production Engineering*, 1/3:321–328.

[57] Ferscha, A., Holzmann, C., Hechinger, M., Emsenhuber, B., Resmerita, S., Vogl, S., Wally, B., 2009, Pervasive Computing, In: Buchberger, B., et al. (eds.), *Hagenberg Research*, Springer, pp. 379–431.

[58] Fine, C.H., Golany, B., Naseraldin, H., 2005, Modeling Tradeoffs in Three-Dimensional Concurrent Engineering: A Goal Programming Approach, *J. of Operations Management,* 23/3-4:389–402.

[59] Fleischmann, B., Meyr, H., 2003, Planning Hierarchy, Modelling and Advanced Planning Systems, In: [37], pp. 457–523.

[60] Foster, I., Kesselman, C., Nick, J.M., Tuecke, S., 2002, Grid Services for Distributed Systems Integration, *IEEE Computer*, 35/6:37–46.

[61] Franceschini, F., Galetto, M., Maisano, D., Mastogiacomo, L., 2009, A Review of Localization Algorithms for Distributed Wireless Sensor Networks in Manufacturing, *Int. J. of Computer Integrated Manufacturing*, 22/7:698–716.

[62] Frei, F.X., 2006, Breaking the Trade-Off Between Efficiency and Service, *Harvard Business Review*, 84/1:92–101.

[63] Goyal, S.K., Giri, B.C., 2001, Recent Trends in Modeling of Deteriorating Inventory, *European J. of Operational Research*, 134:1–16.

[64] Grunow, M., Günther, H.O., Burdenik, H., Alting, L., 2007, Evolving Production Network Structures, *CIRP Annals - Manuf. Tech.*, 56/1:427–430.

[65] Gunasekaran, A., Lai, K.-H., Cheng, T.C.E., 2008, Responsive Supply Chain: A Competitive Strategy in a Networked Economy, *Omega*, 36/4:549–564.

[66] Hara, T., Arai, T., Shimomura, Y., Sakao, T., 2009, Service CAD System to Integrate Product and Human Activity for Total Value, *CIRP J. of Manufacturing Science and Technology*, 1:262–271.

[67] Harms, R., Fleschutz, T., Seliger, G., 2010, Life Cycle Management of Production Facilities Using Semantic Web Technologies, *CIRP Annals - Manuf. Tech.*, 59:45–48.

[68] Hatvany, J., Lettner, F., 1983, The Efficient Use of Deficient Knowledge, *Annals of the CIRP* 32/1:423–426.

[69] Hatvany, J., 1984, Optimizing the Chances of Survival, *Annals of the CIRP*, 33/1:345–346.

[70] Hatvany, J., 1985, Intelligence and Cooperation in Heterarchic Manufacturing Systems, *Robotics and Computer-Integrated Manufacturing*, 2/2:101-104.

[71] Hatvany, J., 1983, Dreams, Nightmares and Reality, *Computers in Industry*, 4/2:109–114.

[72] Hauschild, M. Z., Jeswiet, J., Alting. L., 2005, From Life Cycle Assessment to Sustainable Production: Status and Perspectives. *CIRP Annals - Manuf. Tech.*, 54/2:535–556.

[73] Hauschild, M. Z., Dreyer, L.C., Jørgensen, A., 2008, Assessing Social Impacts in a Life Cycle Perspective—Lessons Learned, *CIRP Annals - Manuf. Tech.*, 57/1:21–24.

[74] Hendler, J., Berners Lee, T., Miller, E., 2002, Integrating Applications on the Semantic Web, *J. of the Institute of Electrical Engineers of Japan*, 122/10:676–680.

[75] Hendricks, K.B., Singhal, V.R., 2005, Association Between Supply Chain Glitches and Operating Performance, *Management Science*, 51/5:695–711.

[76] Holdren, J.P., 2008, Science and Technology for Sustainable Well-Being, *Science*, 319:424–434.

[77] Holland, J.H., 1995, *Hidden Order: How Adaptation Builds Complexity*, Helix Books, Addison-Wesley, New York.

[78] Holvoet, T., Valckenaers, P., 2006, Exploiting the Environment for Coordinating Agent Intentions, Springer LNAI 4389, pp. 51–66.

[79] Homer, Odyssey (XII. 101-114).

[80] Ganek, A.G., Corbi, T.A., 2003, The Dawning of the Autonomic Computing Era, *IBM Systems Journal*, 42/1:5–18.

[81] Huang, G.Q., Zhang, X.Y., Liang, L., 2005, Towards Integrated Optimal Configuration of Platform Products, Manufacturing Processes, and Supply Chains, *J. of Operations Management*, 23/3-4:267–290.

[82] Jansen-Vullers, M.H., van Dorp, C.A., Beulens, A.J.M., 2003, Managing Traceability Information in Manufacture, *Int. J. of Information Management*, 23/5:395–413.

[83] Jeong, W., Nof, S.Y., 2009, A Collaborative Sensor Network Middleware for Automated Production Systems, *Computers & Industrial Engineering*, 57:106–113.

[84] Jovane, F., Koren, Y., Boer, C.R. 2003, Present and Future of Flexible Automation: Towards New Paradigms, *Annals of the CIRP*, 52/2:543–560.

[85] Jovane, F., Yoshikawa, H., Alting, L., Boër, C.R., Westkämper, E., Williams, D., Tseng, M., Seliger, G., Paci, A.M., 2008, The Incoming Global Technological and Industrial Revolution Towards Competitive Sustainable Manufacturing, *CIRP Annals - Manuf. Tech.*, 57/2:641–659.

[86] Kádár, B., Lengyel, A., Monostori, L., Suginishi, Y., Pfeiffer, A., Nonaka, Y., 2010, Enhanced Control of Complex Production Structures by Tight Coupling the Digital and the Physical Worlds, *CIRP Annals - Manuf. Tech.*, 59/1:437–440.

[87] Kaihara, T., Fujii, S., 2006, Virtual Enterprise Coalition Strategy with Game Theoretic Multi-Agent Paradigm, *CIRP Annals - Manuf. Tech.*, 55/1:513–516.

[88] Kapp, R., Aldinger, L., Westkämper, E., 2007, Real-time Factory Cockpit System; Implementation and Assurance of Economic Transformability, *Proc. of the 20st st Computer-Aided Production Engineering*, June 6-8, Glasgow, Scotland, UK, pp. 99–108.

[89] Kara, S., Manmeka, S., Herrmann, C., 2010, Global Manufacturing and the Embodied Energy of Products, *CIRP Annals - Manuf. Tech.*, 59/1:29–32.

[90] Karnok, D., Monostori, L., 2010, Routing Model Refinement in Large-scale Manufacturing Environment by Using Data Mining, *Proc. of the 43rd CIRP Int. Conf. on Manufacturing Systems*, May 26-28, Vienna, Austria. pp. 725–734.

[91] Kemény, Zs., Erdős, G., Váncza, J., 2008, Representation and Navigation Techniques for Semi-Structured Knowledge in Collaborating Communities. In: [16] pp. 185–212.

[92] Kiritsis, D., 2011, Closed-Loop PLM for Intelligent Products in the Era of the Internet of Things, *Computer-Aided Design*, 43/5:479–501.

[93] Kluge, S., Riffelmacher, P., Hummel, V., Constantinescu, C., Westkämper, E., 2008, Self-learning and Self-optimizing Assembly Systems, In: *Proc. of 2nd CIRP Conf. on Assembly Technologies and Systems*, Toronto, Canada, pp. 221–230.

[94] Koren, Y., 2010, *The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems*, Wiley.

[95] Koren, Y., Heisel, Z., Jovane, F., Moriwaki, M., Pritschow, G., Ulsoy, G., van Brussel, H., 1999, Reconfigurable Manufacturing Systems, *CIRP Annals - Manuf. Tech.*, 48/2:527–540.

[96] Kouvelis, P., Chambers, C., Wang, H., 2006, Supply Chain Management Research and Production and Operations Management: Review, Trends, and Opportunities, *Production and Operations Management*, 15/3:449–470.

[97] Kumara, S.R.T., Ranjan, P., Surana, A., Narayanan, V., 2003, Decision Making in Logistics: A Chaos Theory Based Analysis, *CIRP Annals - Manuf. Tech.*, 52/1:381–384.

[98] Kumaz, S., Cohn, A., Koren, Y., 2005, A Framework for Evaluating Production Policies to Improve Customer Responsiveness, *CIRP Annals - Manuf. Tech.*, 54/1:401–406.

[99] Laffont, J.J., Martimort, D., 2001, *The Theory of Incentives*, Princeton University Press.

[100] Lanza, G., Ude, J., 2010, Multidimensional Evaluation of Value Added Networks. *CIRP Annals - Manuf. Tech.* 59/1:489–492.

[101] Leitao, P., Restivo, F.J., 2006, ADACOR: A Holonic Architecture for Agile and Adaptive Manufacturing Control, *Computers in Industry*, 57/2:121–130.

[102] Leng, M., Parlar, M., 2005, Game Theoretic Applications in Supply Chain Management: A Review, *INFOR*, 43/3:187–220.

[103] Li, X., Wang, Q., 2007, Coordination Mechanisms of Supply Chain Systems, *European J. of Operational Research*, 179/1:1–16.

[104] Linnaeus, C., 1735, *Systema Naturae*, Lugduni Batavorum.

[105] Liu, Y., Luo, Y., Liu, T., 2009, Governing Buyer-Supplier Relationships through Transactional and Relational Mechanisms: Evidence from China, *J. of Operations Management*, 27/4:294–309.

[106] Lu, S.Y.-C., Elmaraghy, W., Schuh, G., Wilhelm, R., 2007, A Scientific Foundation of Collaborative Engineering, *CIRP Annals - Manuf. Tech.*, 56/2:605–634.

[107] Lubchenco, J., 1998, Entering the Century of the Environment: A New Social Contract for Science, *Science*, 279:491–497.

[108] Luck, M., McBurney, P., Shehory, O., et al. 2005, *Agent Technology: Computing as Interaction. A Roadmap for Agent-Based Computing*, AgentLink III, http://www.agentlink.org/roadmap/al3rm.pdf, accessed at 2010.08.13.

[109] Lucke, D., Constantinescu, C., Westkämper, E., 2008, Smart Factory - A Step Towards the Next Generation of Manufacturing, *Proc. of the 41rd CIRP Int. Conf. on Manufacturing Systems*, Tokyo, Japan, pp. 115–118.

[110] Lucke, D., Constantinescu, C., Westkämper, E., 2009, Context Data Model, the Backbone of a Smart Factory, In: *Sustainable Development of Manufacturing Systems, Proc. of the 42nd CIRP Conf. on Manufacturing Systems*, Grenoble, France.

[111] Lutters, D., Mentink, R.J., van Houten, F.J.A.M., Kals, H.J.J., 2001, Workflow Management Based on Information Management, *CIRP Annals - Manuf. Tech.*, 50/1:309–312.

[112] Márkus, A., Kis, T., Váncza, J., Monostori, L., 1996, A Market Approach to Holonic Manufacturing, *CIRP Annals - Manuf. Tech.*, 45/1:433–436.

[113] Márkus, A., Váncza, J., 1998, Product Line Development with Customer Interaction, *CIRP Annals - Manuf. Tech.,* 47/1:361–364.

[114] Maropoulos, P.G., 2002, Digital Enterprise Technology—Defining Perspectives and Research Priorities, *Proc. of the 1st CIRP Seminar on Digital Enterprise Technology*, Durham, UK, Part V:3–12.

[115] Maropoulos, P.G., Kotsialos, A., Bramall, D.G., 2006, A Theoretical Framework for the Integration of Resource Aware Planning with Logistics for the Dynamic Validation of Aggregate Plans within a Production Network, *CIRP Annals - Manuf. Tech.*, 55/1:483–486.

[116] Marsh, D., Tynan, R., O'Kane, D., O'Hare, G.M.P., 2004, Autonomic Wireless Sensor Networks, *Engineering Applications of Artificial Intelligence*, 17:741–748.

[117] Mas-Colell, A., Whinston, M.D., Green, J.R., 1995, *Microeconomic Theory*, Oxford University Press.

[118] Mazzola, E., Bruccoleri, M, Perrone, G., 2009, A Strategic Framework for Firm Networks in Manufacturing Industry: An Empirical Survey, *CIRP Annals - Manuf. Tech.*, 58/1:387–390.

[119] McFarlane, D., Sarma, S., Chirn, J.L., Wong, C.Y., Ashton K., 2003, Auto ID systems and intelligent manufacturing control, *Engineering Applications of Artificial Intelligence*, 16/4:365–376.

[120] Meier, H., Golembiewski, M., Zoller, C.S., 2006, Design Method and Software Architecture for Federal SME Production Networks, *CIRP Annals - Manuf. Tech.*, 55/1:517–520.

[121] Meier, H., Roy, R., Seliger, G., 2010, Industrial Product-Service systems-IPS^2, *CIRP Annals - Manuf. Tech.*, 59/2:607–627.

[122] Menzel, W., 2010, A Radically New Automotive Manufacturing Concept, *Proc. of Transport Research Arena Europe 2010*, Brussels.

[123] Monostori, L., 2003, AI and Machine Learning Techniques for Managing Complexity, Changes and Uncertainties in Manufacturing, *Engineering Applications of Artificial Intelligence*, 16/4:277–291.

[124] Monostori, L., Csáji, B.Cs., 2006, Stochastic Dynamic Production Control by Neurodynamic Programming, *CIRP Annals - Manuf. Tech.*, 55/1:473–478.

[125] Monostori, L., Csáji, B.Cs., Kádár, B., 2004, Adaptation and Learning in Distributed Production Control, *CIRP Annals - Manuf. Tech.*, 53/1:349–352.

[126] Monostori, L., Kádár, B., Pfeiffer, A., Karnok, D., 2007, Solution Approaches to Real-Time Control of Customized Mass Production, *CIRP Annals - Manuf. Tech.*, 56/1:431–434.

[127] Monostori, L., Kemény, Zs., Ilie-Zudor, E., Szathmári, M., Karnok, D., 2009, Increased Transparency within and beyond Organizational Borders by Novel Identifier-Based Services for Enterprises of Different Size, *CIRP Annals - Manuf. Tech.*, 58/1:417–420.

[128] Monostori, L., Kis, T., Váncza, J., Kádár, B., Erdős, G. 2009, Real-time, Cooperative Enterprises for Customized Mass Production, *Int. J. of Computer Integrated Manufacturing*, 22/1:55–68.

[129] Monostori, L., Márkus, A., Van Brussel, H., Westkämper, E. 1996, Machine Learning Approaches to Manufacturing, *CIRP Annals - Manuf. Tech.*, 45/2:675–712.

[130] Monostori, L., Váncza, J., Kumara, S., 2006, Agent-Based Systems for Manufacturing, *CIRP Annals - Manuf. Tech.*, 55/2:697–720.

[131] Mourtzis, D., Papakostas, N., Makris, S., Xantakis, V., Chryssolouris, G., 2008, Supply Chain Modeling and Control for Producing Highly Customized Products, *CIRP Annals - Manuf. Tech.*, 57/1:451–454.

[132] Muller, A., Marquez, A.C., Iung, B., 2008, On the Concept of E-Maintenance: Review and Current Research, *Reliability Engineering and System Safety*, 93:1165–1187.

[133] Nagarajan, M., Sošić, G., 2008, Game-Theoretic Analysis of Cooperation Among Supply Chain Agents: Review and Extensions, *European J. of Operational Research*, 187/3:719-745.

[134] Narahari, Y., Garg, D., Narayanam, R., Prakash, H., 2009, *Game Theoretic Problems in Network Economics and Mechanism Design Solutions*, Springer, London.

[135] Narayanan, V.G., Raman, A., 2004, Aligning Incentives in a Supply Chain, *Harvard Business Review*, November 2004:94–102.

[136] Nisan, N., 2007, Introduction to Mechanism Design, In: Nisan, N., Roughgarden, T., Tardos, É., Vazirani, V.V. (eds.), *Algorithmic Game Theory*, Cambridge University Press, pp. 209–241.

[137] Nishiguchi, T., Beaudet, A., 1998, The Toyota Group and the Aisin Fire, *Sloan Management Review*, 40/1:49–59.

[138] Nishino, N., Ueda, K., Sato, Y., 2010, Modeling of Decision Making in Membership Services as Public Goods Problems, *CIRP Annals - Manuf. Tech.*, 59/1:473–476.

[139] Nonaka, I., Takeuchi, H., 1995, *The Knowledge-Creating Company*, Oxford University Press.

[140] Nowak, M.A., 2006, Five Rules for the Evolution of Cooperation, *Science*, 314:1560–1563.

[141] Nowak, M.A., Sigmund, K., 2005, Evolution of Indirect Reciprocity, *Nature*, 437:1291–1298.

[142] N.N., 2005, *ITU Internet Reports 2005: The Internet of Things*, Int. Telecommunication Union (ITU), Geneva.

[143] Nyhuis, P., Wiendahl, H.-P., 2006, Logistic Production Operating Curves - Basic Model of the Theory of Logistic Operating Curves, *CIRP Annals - Manuf. Tech.*, 55/1: 441–444.

[144] Ostrom, E., 2009, A General Framework for Analyzing Sustainability of Social-Ecological Systems, *Science*, 325:419–422.

[145] Papakostas, N., Mourtzis, D., 2007, An Approach for Adaptability Modeling in Manufacturing - Analysis Using Chaotic Dynamics, *CIRP Annals - Manuf. Tech.*, 56/1:491–494.

[146] Parlikad, A.K., McFarlane, D., 2007, RFID-based Product Information in End-of-Life Decision Making, *Control Engineering Practice*, 15/11:1348–1363.

[147] Perakis, G., Roels, G., 2007, The Price of Anarchy in Supply Chains: Quantifying the Efficiency of Price-Only Contracts, *Management Science*, 53/8:1249–1268.

[148] Petersen, K.J., Handfield, R.B., Ragatz, G.L., 2005, Supplier Integration into New Product Development: Coordinating Product, Process and Supply Chain Design, *J. of Operations Management*, 23/3-4:371–388.

[149] Pochet Y., Wolsey, L.A., 2006, *Production Planning by Mixed Integer Programming*, Springer.

[150] Prahalad, C.K., Venkat Ramaswamy, 2004, Co-creation Experiences: The Next Practice in Value Creation, *J. of Interactive Marketing*, 18/3:5–14.

[151] Raghavan, U.N., Kumara, S.R.T., 2007, Decentralised Topology Control Algorithms for Connectivity of Distributed Wireless Sensor Networks, *Int. J. Sensor Networks*, 2/3-4:201–210.

[152] Rand, D., Nowak, M.A., 2009, Name and Shame, *New Scientist*, 14 November:28-29.

[153] Rigby, D.K., Vishwanath, V., 2006, Localization: The Revolution in Consumer Markets, *Harvard Business Review*, 84/4:82–92.

[154] Roussos, G., Kostakos, V., 2009, RFID in Pervasive Computing: State-of-the-Art and Outlook, *Pervasive and Mobile Computing*, 5:110–131.

[155] Saint Germain, B., 2011, *Applying Trust Mechanisms in Networked Production Control*, PhD thesis. K.U. Leuven, forthcoming.

[156] Salanié, B., 2005, *The Economics of Contracts*, *a Primer*, (second edition), MIT Press.

[157] Sandberg, E., 2007, Logistics Collaboration In Supply Chains: Practice vs. Theory, *Int. J. of Logistics Management*, 18/2:274–293.

[158] Schilling, M.A., Phelps, C.C., 2007, Interfirm Collaboration Networks: The Impact of Large-Scale Network Structure on Firm Innovation, *Management Science*, 58/7: 1113–1126.

[159] Scholz-Reiter, B., Freitag, M., 2007, Autonomous Processes in Assembly Systems, *CIRP Annals - Manuf. Tech.*, 56/2:712–729.

[160] Scholz-Reiter, B., Görges, M., Philipp, T., 2009, Autonomously Controlled Production Systems – Influence of Autonomous Control Level on Logistic Performance, *CIRP Annals - Manuf. Tech.*, 58/1:395–398.

[161] Scholz-Reiter, B., Rekersbrink, H., Görges, M., 2010, Dynamic Flexible Flow Shop Problems – Scheduling Heuristics vs. Autonomous Control, *CIRP Annals - Manuf. Tech.*, 59/1:465–468.

[162] Schönsleben, P., 2009, Changeability of Strategic and Tactical Production Concepts, *CIRP Annals - Manuf. Tech.*, 58/1:383–386.

[163] Schönsleben, P., 2011, *Integral Logistics Management - Operations and Supply Chain Management Within and Across Companies*, 4th edition, Auerbach -Taylor & Francis.

[164] Schuh, G,. 2006, Sm@rt Logistics: Intelligent Networked Systems, *CIRP Annals - Manuf. Tech.*, 55/1:505–508.

[165] Schuh, G., Gottschalk, S., Höhne, T., 2007, High Resolution Production Management, *CIRP Annals - Manuf. Tech.*, 56/1:439–442.

[166] Schuh, G., Kampker, A., Narr, C., Potente, T., Attig, Ph., 2008, myOpenFactory, *Int. J. of Computer Integrated Manufacturing*, 21/2:215 – 221.

[167] Schuh, G., Monostori, L., Csáji, B.Cs., Döring, S., 2008, Complexity-based Modeling of Reconfigurable Collaborations in Production Industry, *CIRP Annals - Manuf. Tech.*, 57/1:445–450.

[168] Shapeways portal, www.shapeways.com, accessed at 2011.04.22.

[169] Seliger, G., Zettl, M., 2008, Modularization as an Enabler for Cycle Economy, *CIRP Annals - Manuf. Tech.*, 57/1:133–136.

[170] Shen, W., Hao, Q., Wang, S., Li, Y., Ghenniva, H., 2007, An Agent-Based Service-Oriented Integration Architecture for Collaborative Intelligent Manufacturing, *Robotics and Computer Integrated Manufacturing*, 23:315–325.

[171] Shoham, Y., Leyton-Brown, K., 2009, *Multiagent Systems: Algorithmic, Game-Theoretic, and Logical Foundations*, Cambridge Univ. Press.

[172] Sihn, W., Bischoff, J., Palm, D., 2004, The 5-Days-Car: Increasing Agility in the Automotive Supply Chain, *Proc. of DAAAM 2004 Conf.*, pp. 415–416.

[173] Sihn, W., Schmitz, K., 2007, Extended Multi-Customer Supplier Parks in the Automotive Industry, *CIRP Annals - Manuf. Tech.*, 56/1:479–482.

[174] Simchi-Levi, D., 2010, *Operations Rules: Delivering Value through Flexible Operations*, MIT Press.

[175] Surana, A., Kumara, S., Greaves, M., Raghavan, U.N., 2005, Supply-Chain Networks: A Complex Adaptive Systems Perspective, *Int. J. of Production Research*, 43/20:4235–4265

[176] Stadtler, H., 2005, Supply Chain Management and Advanced Planning – Basics, Overview and Challenges, *European J. of Operational Research*, 163:575–588.

[177] Stadtler, H., 2009, A Framework for Collaborative Planning and State-of-the-Art, *OR Spectrum*, 31:5–30.

[178] Steritt, R., Parashar, M., Tianfield, H., Unland, 2005, A Concise Introduction to Autonomic Computing, *Advanced Engineering Informatics*, 19:181–187.

[179] Swaminathan, J.M., Tayur, S.R. 2003, Models for Supply Chains in E-Business, *Management Science*, 49/10:1387–1406.

[180] Tang, S.C., 2006, Perspectives in Supply Chain Risk Management, *Int. J. of Production Economics*, 103/3:451–488.

[181] Tao, F., Zhang, L., Zhang, Z.H., Nee, A.Y.C., 2010, A Quantum Multi-Agent Evolutionary Algorithm for Selection of Partners in a Virtual Enterprise, *CIRP Annals - Manuf. Tech.*, 59/1:485–488.

[182] Tempelmeier, H., 2006, *Inventory Management in Supply Networks: Problems, Models, Solutions*, Books-on-Demand, Norderstedt.

[183] ten Dam, D.C., Anema, H.F.A., van Houten, F.J.A.M., Lutters, D., 2009, CNC Worknet: A Network of Flexible Production Plants, *Proc. of the CIRP Conf. on Manufacturing Systems*, Grenoble, France.

[184] ten Dam, D.C., Lutters, D., 2010, An Approach to Workflow Based Quality Management, *Proc. of the 43rd CIRP Int. Conf. on Manufacturing Systems*, Vienna, Austria, pp. 975–982.

[185] Tirole, J., 1988, *The Theory of Industrial Organization*, MIT Press.

[186] Thadakamalla, H.P., Ranghava, U.N., Kumara, S., Albert, R. 2004, Survivability of Multiagent-Based Supply Networks: A Topological Perspective, *IEEE Intelligent Systems*, 19/5:24–31.

[187] Tolio, T., Ceglarek, D., ElMaraghy, H.A., Fischer, A., Hu, S.J., Laperrière, L., Newman, S.T., Váncza, J., 2010, SPECIES – Co-evolution of Products, Processes and Production Systems, *CIRP Annals - Manuf. Tech.*, 59/2:672–693.

[188] Tomiyama, T., Gu, P., Jin, Y., Lutters, D., Kind, Ch., Kimura, F. 2009, Design Methodologies: Industrial and Educational Applications, *CIRP Annals - Manuf. Tech.,* 58/2:543–565.

[189] Tseng, M.M., Du, X., 1998, Design by Customers for Mass Customization Products, *CIRP Annals - Manuf. Tech.*, 47/1:103–106.

[190] Tseng, M.M., Jiao, R.J., Wang, C., 2010, Design for Mass Personalization, *CIRP Annals - Manuf. Tech.*, 59/1:175–178.

[191] Tseng, M.M., Kjellberg, T., Lu, S.C.-Y., 2003, Design in the New e-Commerce Era, *CIRP Annals - Manuf. Tech.*, 52/2:509–519.

[192] Tseng, M.M., Lei, M., Su, C., Merchant, M.E., 1997, A Collaborative Control System for Mass Customization Manufacturing, *CIRP Annals - Manuf. Tech.*, 46/1:373–376

[193] Ueda, K., Kito, T., Takenaka, T., 2008, Modelling of Value Creation Based on Emergent Synthesis, *CIRP Annals - Manuf. Tech.,* 57/1:473–476.

[194] Ueda, K., Lengyel, A., Hatono, I., 2004, Emergent Synthesis Approaches to Control and Planning in Make to Order Manufacturing Environments, *CIRP Annals - Manuf. Tech.*, 53/1:385–388.

[195] Ueda, K., Márkus, A., Monostori, L., Kals, H.J.J., Arai, T., 2001, Emergent Synthesis Methodologies for Manufacturing, *CIRP Annals - Manuf. Tech.*, 50/2: 535–551.

[196] Ueda, K., Takenaka, T., Váncza, J., Monostori, L., 2009, Value Creation and Decision-Making in Sustainable Society, *CIRP Annals - Manuf. Tech.*, 58/2:681–700.

[197] Ueda, K., Vaario, J., Ohkura, K.H., 1997, Modelling of Biological Manufacturing Systems for Dynamic Reconfiguration, *CIRP Annals - Manuf. Tech.* 46/1:343–346.

[198] Ueda, K., Vaario, J., Takeshita, T., Hatono, I., 1999, An Emergent Synthetic Approach to Supply Networks, *CIRP Annals - Manuf. Tech.*, 48/1:377–380.

[199] Uys, W., DuPreez, N.D., Lutters, D., 2010, Leveraging Unstructured Information in Support of Innovation, In: Dimitrov, D. (ed.), *COMA'10; Int. Conf. on Competitive Manufacturing*, pp. 335–340.

[200] Valckenaers, P., Van Brussel, H., 2005, Holonic Manufacturing Execution Systems, *CIRP Annals - Manuf. Tech.*, 54/1:427–432.

[201] Valckenaers, P., Van Brussel, H., Verstraete, P., Saint Germain, B., Hadeli, 2007, Schedule Execution in Autonomic Manufacturing Systems, *J. of Manufacturing Systems*, 26:75–84.

[202] Valente, A., Carpanzano, E., Nassehi, A., Newman, S., 2010, A STEP Compliant Knowledge Based Schema to Support Shop-Floor Adaptive Automation in Dynamic Manufacturing Environments, *CIRP Annals - Manuf. Tech.*, 59/1:441–444.

[203] Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L., Peeters, P., 1998, Reference Architecture for Holonic Manufacturing Systems: PROSA, *Computers in Industry*, 37:255–274.

[204] Van Landeghem, H., Vanmaele, H., 2002, Robust Planning: A New Paradigm for Demand Chain Planning, *J. of Operations Management* 20:69–783.

[205] Vargo, S.L, Maglio, P.P., Akaka, M.A., 2008, On Value and Value Co-Creation: A Service Systems and Service Logic Perspective, *European Management J.*, 26:145–152.

[206] Váncza, J., Egri, P., 2006, Coordinating Supply Networks in Customized Mass Production – A Contract-Based Approach, *CIRP Annals - Manuf. Tech.*, 55/1:489–492.

[207] Váncza, J., Egri, P., Karnok, D., 2010, Planning in Concert: A Logistics Platform for Production Networks, *Int. J. of Computer Integrated Manufacturing*, 23/4:297–307.

[208] Váncza, J., Egri, P., Monostori, L., 2008, A Coordination Mechanism for Rolling Horizon Planning in Supply Networks, *CIRP Annals - Manuf. Tech.*, 57/1:455–458.

[209] Váncza, J., Márkus, A., 2000, An Agent Model for Incentive-Based Production Scheduling, *Computers in Industry*, 43/2:173–187.

[210] Verstraete, P., Saint Germain, B., Valckenaers, P., Van Brussel, H., Van Belle, J., Hadeli, K., 2008, Engineering Manufacturing Control Systems Using PROSA and Delegate MAS, *Int. J. of Agent-Oriented Software Engineering*, 2:62–89.

[211] Wagner, C., Nyhuis, P., 2009, A Systematic Approach to Analysis and Design of Global Production Networks, *Prod. Eng. Res. Devel*., 3:295–303.

[212] Wang, Y., Tseng, M.M., 2008, Incorporating Probabilistic Model of Customers' Preferences in Concurrent Engineering, *CIRP Annals - Manuf. Tech.*, 57/1:137–140.

[213] Warnecke, H.J., 1997, *The Fractal Factory: Revolution in Corporate Culture*, Springer.

[214] Wegner, P., 1997, Why Interaction is More Powerful than Algorithms, *Communications of the ACM*, 40/5: 80–91.

[215] Wenstop, F., Koppang, H., 2009, On Operations Research and Value Conflicts, *Omega*, 37/6:1109–1120.

[216] Whang, S., 2010, Timing of RFID Adoption in a Supply Chain, *Management Science*, 56/2:343–355.

[217] Whipple, J.M., Russell, D., 2007, Building Supply Chain Collaboration: A Typology of Collaborative Approaches, *Int. J. of Logistics Management*, 18/2:174–196.

[218] Wiendahl, H.-P., ElMaraghy, H.A., Nyhuis, P., Zah, M.F., Wiendahl, H.-H., Duffie, N., Brieke, M., 2007, Changeable Manufacturing - Classification, Design and Operation, *CIRP Annals - Manuf. Tech.*, 56/2:783–809.

[219] Wiendahl, H.-P., Lutz, S., 2002, Production in Networks, *CIRP Annals - Manuf. Tech.*, 51/2:573–586.

[220] Wiendahl, H.-P., von Cieminski, G., Begemann, C., 2003, A Systematic Approach for Ensuring the Logistic Process Reliability of Supply Chains, *CIRP Annals - Manuf. Tech.*, 52/1:375–380.

[221] Wilhelm, R.G., Chandrashekar, R., Sun, R., Hegedus, M., Chu, B., Tolone, W.J., Long, J., 2000, Finite Schedule Monitoring and Filtering in a Computer Integrated Manufacturing Environment, *CIRP Annals - Manuf. Tech.*, 49/1:335–338.

[222] Yan, J., Ye, K., Wang, H., Hua, Z., 2010, Ontology of Collaborative Manufacturing: Alignment of Service-Oriented Framework with Service-Dominant Logic, *Expert Systems with Applications*, 37:2222–2231.

[223] Yoo, J., Kumara, S.R.T., 2010, Implications of K-best Modular Product Design Solutions to Global Manufacturing, *CIRP Annals - Manuf. Tech.*, 59/1:481–484.

[224] Young, O.R., Berkhout, F., Gallopin, G.C., Janssen, M.A., Ostrom, E., van der Leeuw, S., 2006, The Globalization of Socio-Ecological Systems: An Agenda for Scientific Research, *Global Environmental Change*, 16/3:304–316.

[225] Yoshikawa, H., 2008, Sustainable Manufacturing, in: *Evening Seminar in the 41st CIRP Conf. on Manufacturing Systems*, May 27, 2008, Tokyo, Japan, http://www.nml.t.u-tokyo.ac.jp/cirpms08.

[226] Zaeh, M.F., Ostgathe, M., Lau, C., Wiesbeck, M., 2009, Adaptive, Product-based Control of Production Processes, *Proc. of the 3rd Int. Conf. on Changeable, Agile, Reconfigurable and Virtual Production CARV-09*, Munich, Germany, pp. 99–110.

[227] Zaeh, M.F., Reinhart, G., Ostgathe, M., Geiger, F., Lau, C., 2010, A Holistic Approach for the Cognitive Control of Production Systems, *Advanced Engineering Informatics*, 24/3:300–307.

[228] Zaharudin, A.A., Wong, C.Y., Agarwal, V., McFarlane, D., Koh, R., Kang, Y., 2002, The Intelligent Product Driven Supply Chain, White Paper, Auto-ID-Centre, University of Cambridge, UK, p. 21.

[229] Zhuang, L.Q., Zhang, D.H., Wong, M.M., 2010, Wireless Sensor Networks for Networked Manufacturing Systems, In: Silvester-Blanes, J., *Factory Automation, inTech*, Chapter 7, p. 22.

[230] Zuehlke, D., 2010, SmartFactory – Towards a Factory-of-Things, *Annual Reviews in Control*, 34:129–138.