ICT as Critical Driver -
Post Mass Production Paradigm (PMPP) Trajectories

Hermann Kühnle

Otto-von-Guericke-University Magdeburg ,Universitätsplatz 2, 39196 Magdeburg Germany,

Centre for Extended Enterprises CE2
Phone:0049(0)391/67-18517
Fax:0049(0)391/67-12404

E-mail: CE2@mb.uni-magdeburg.de
E-mail: hermann.kuehnle@mb.uni-magdeburg.de
Internet: http://www.uni-magdeburg.de/iaf

Abstract

Within the past decades, developments in manufacturing have been turbulent and radical. For the manufacturing and management sciences, revolutionary changes took place. Based on Kuhn's findings on the nature of scientific revolutions, the paper consolidates projections for future developments in manufacturing by exploiting interactions of the most important drivers of these developments. Major trajectories are drawn, considered to be significant for future manufacturing structures using expert session results on manufacturing scenarios. Effects of Information and Communication Technologies (ICT) are strongly emphasised. The outline intends to support strategic decision making in manufacturing companies. The methods sketched and applied with groups of scientists, experts and companies' executives can be adopted for individual company strategy definitions.

Introduction

Industrial production is undergoing a considerable change in consequence of shifts in conditions, technological progresses and improving infrastructures. Pressurised by the results of Lean Manufacturing, (Ohno 1988, Womack et al. 1990, Bennett 1996, Liker 2003), accustomed Mass Production reached limits. Fewer restrictions, faster developments of markets and technology spread have modified the basic assumptions for mass production and shifted the scientific paradigm. Exhaustive Post Mass Paradigm (PMPP) work has been done within the IMS/GNOSIS project (IMS program initiated by MITI, more than 100 partners involved), based on the general perception, that not just technology and markets but especially social impacts and increasing availability of resources anywhere and anytime trigger these developments strongly. The general believe was that Mass Production of the familiar type is bound to run into trouble globally. There was a wide perception that the established scientific paradigm[1] hits limits; observed phenomena could not be explained by application of existent theories. The Gnosis (Knowledge Systematisation in Manufacturing) approach (GNOSIS, 1994) interpreted all observations on the basis of Kuhn's Theory of Scientific Revolutions (Kuhn, 1962) for post mass production, critical drivers and main restrictions could be identified in order to determine expected developments for the global future of manufacturing.

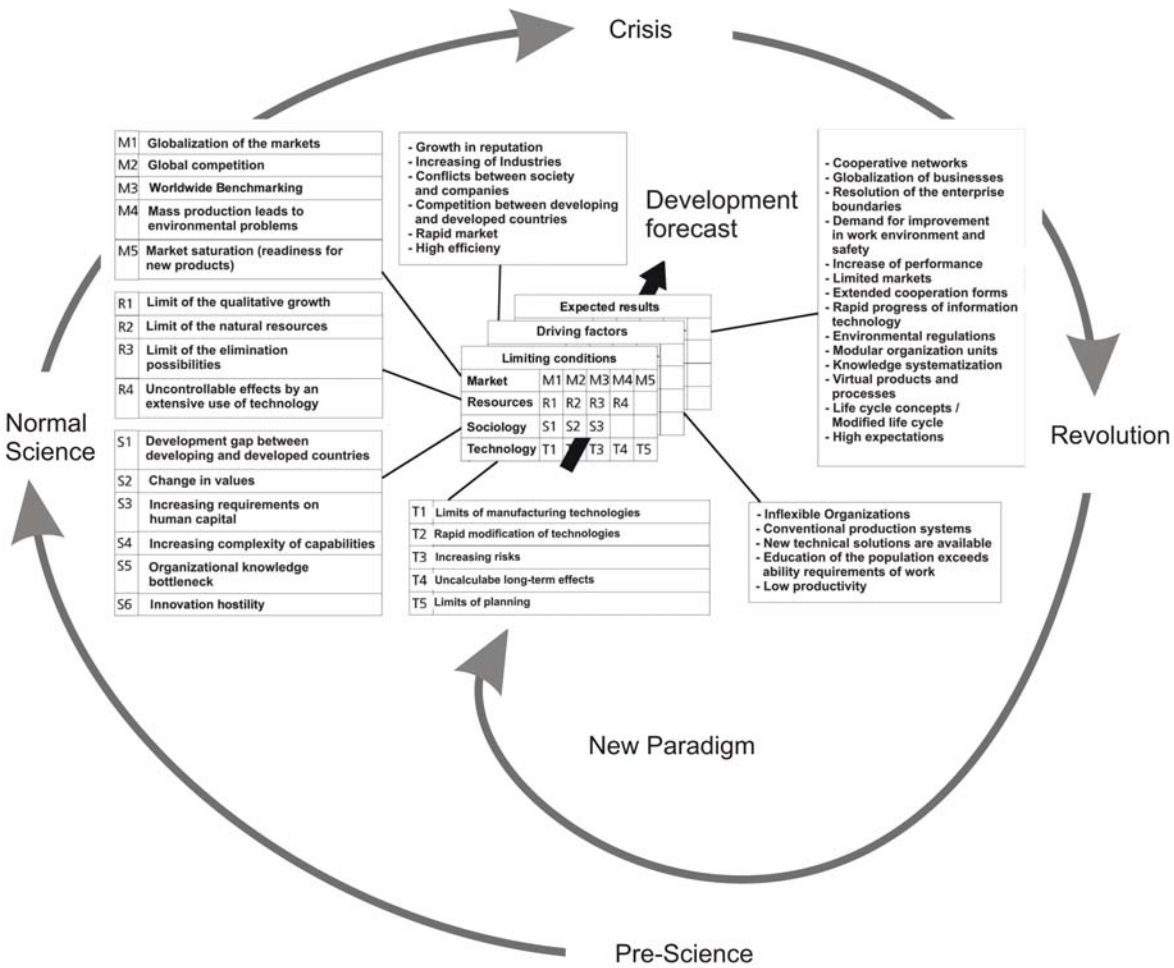

Figure 1: Gnosis (Knowledge Systemisation in Manufacturing) development approach following Kuhn's theory of scientific revolutions

The objective was to establish forecasts for appropriate enabling technologies and methods of communication as well as knowledge sharing across the boundaries of companies, technical domains, nations, time and space. These forecasts were basic inputs to explain the mechanisms for new manufacturing management principles. Central point of all findings was

[1] A paradigm is considered a thought pattern or a general way of envisioning contexts in a scientific discipline

that saturated markets and decentralised availability of knowledge were the main drivers of the events (Figure 1). Resulting frameworks included soft artefacts, (Tomiyama, 1997), virtual manufacturing, (Kuehnle & Martinez, 2000), knowledge management and enabling technologies and integration (Gaines et al. 1995).

In the practical field, a number of new management approaches and production principles could be observed, containing elements of the PMPP; impotant steps were to overcome the tayloristic functional principle of labour division. The most important manufacturing philosophies presented were Agile Manufacturing (Kidd 1994, Goldman et al. 1995), Holonic Manufacturing (VanBrussels et al. 1998, Deen 2003, Brennan et al., 2005), Bionic Manufacturing (Okino 1993, Ueda 1996) and Fractal Factory (Kuehnle 1995, Kuehnle&Schmelzer 1995). Emphasis was set at renewal of companies culture, -organization and –management. Main feature was that human creativity and improvisation was given higher decision power.

Meanwhile experience shows that all concepts developed face difficulties in implementation because of the impossibility to handle complexity (Webb et al. 2005), so inter organizational structures were configured as Supply Chains, Virtual enterprises, Extended Enterprises (Camarinha –Matos & Afsamanesh, 2005) pointing at the emergence of a strongly ICT supported networked manufacturing world. To answer questions about the nature this new manufacturing world, additional work was carried out within the last 2 years exploiting the interrelations of the trends and drivers elaborated.

The cross impacts of driving forces - the integrated approach

Continued trade liberalisation and reductions in barriers to trade have accelerated international flows of information, goods and services. The major impact on manufacturers has been the higher availability of resources as low-cost labour and manufacturing capacity, increasingly compelling to move towards sourcing parts and components globally (NGM 1997). Other key driving forces were identified as shortening product lifecycles placing a premium on speed to market; rapid declining costs of transportations and communications and especially social issues (Anderson&Bunce 2000).

Nevertheless most forecasts on developments of manufacturing have been one-dimensional technology based. The Gnosis work has provided a set up to sketch forecasts on the base of a multidimensional view. It differs from the Eclectic Paradigm, the probably most important

(Kuhn, 1962)

multi-causal approach so far, covering three aspects (OLI), (Dunning 1993). Four driver fields: Market, Social Impact, Resources and Technology are regarded. It aims at results thatt are valid on a global scale, and are not restricted to local/national perspectives.

Evolution and innovation in manufacturing is thus also to be viewed as a social process that is linked with technologies or technical systems, resources as well as with markets. While many considerations were based on the on the assumptions of driving multiple forces, independent from each other, it seems to become more and more evident, that the driving forces influence each other (Figure 2). Research on innovation has to acknowledge as well that the social and political systems, markets, technologies as well as resources are heavily interacting (Lundvall, 1988).

Markets or the existence of technologies (knowledge) may attract resources and create a climate of social acceptance.

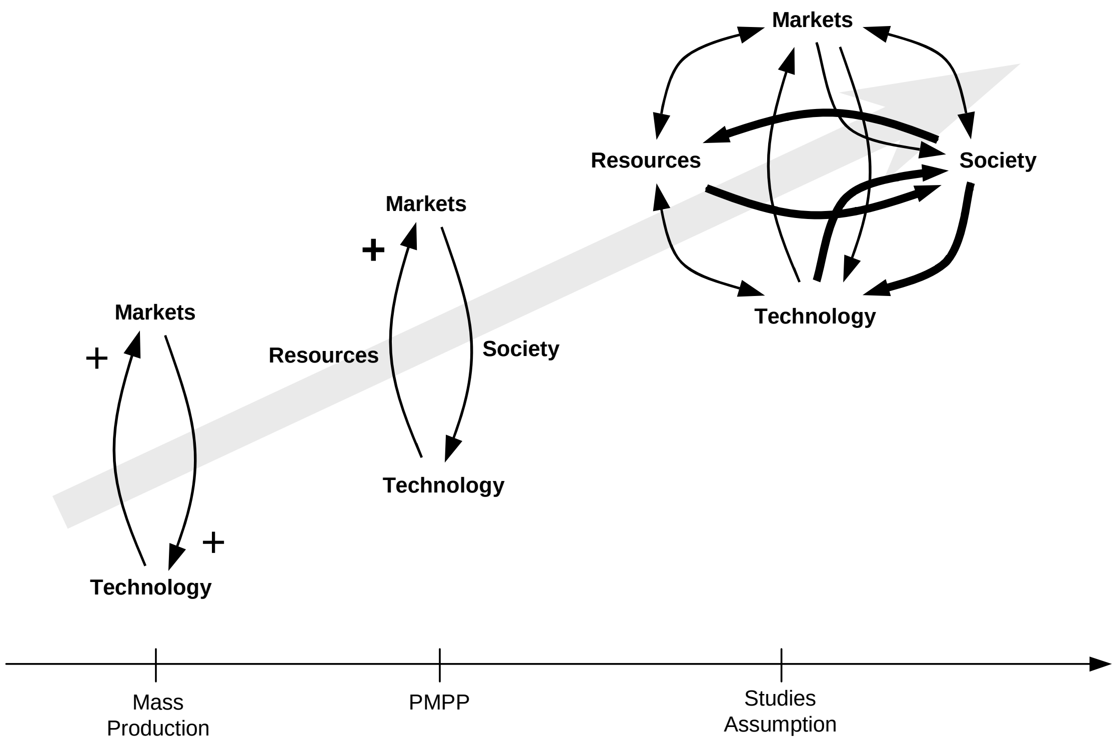

Figure 2: Evolution of driving factors and their interrelations and assignments to Production Frameworks; emphasised interrelations, detailed in subsequent outline

On the other hand overheated progress of technologies may generate constellations were big markets simply “ignore” the existence of extremely useful new products. Especially the use of advanced ICT devices in networked environments causes considerable efforts to reach higher acceptance. Also these difficulties have brought up discussions about the import role of national innovation systems NIS and regional innovation systems (RIS) as specific interpretations of systems innovation (Freeman, 1995), with strong cross impacts between different innovation fields. There is significant evidence that within the PMPP all drivers regarded have to be interpreted as interrelated/linked entities. A workshop based (4F) method (EVOLUTION) for synthesising these interdependencies has been applied to discuss strategic issues for the future of manufacturing companies. Based on cross impacts and links between the trends and drivers, company specific trajectories can be determined and evaluated for strategy formulation. Trends with crucial and limiting impact may be selected to determine parameters and values for strategic early warning.

Trajectory Forecast

An enormous amount of attention is drawn to surveys on “new” concepts of manufacturing, which technology progresses will provide. The general over-optimism in the take-up of predicted technologies however makes these technological forecasts deliver much less than promised. Time lags, market failures or path dependencies (sunk costs, institutional rigidities, and network effects engaging older technologies) that affect adoptions are important causes (Shapira et al. 2004). Moreover believes in societies as well as human resources education and training levels become crucial factors defining the speed of the developments.

In this outline, the trajectories proposed will not primarily consist of technological components. The focus will be on the study of cross impacts of technology on other key drivers. However all application cases showed that a common base of understanding about the technological possibilities should be provided as a start. Therefore, some of the most important technology trends are sketched, having impact on the future of manufacturing in order to make aware of the technical potential involved. More and new trends can always be added by exploiting publicly accessible data[2]. Based on these inputs, workshops may be started with the objective to synthesise trajectories.

Technology Forecast Input

Concerns about low-cost competitors drove technological forecasts, to emphasise the adoption of high value, innovative manufacturing approaches by

- new product development technologies such as modelling and simulation,

[2] As http: //trendchart.cordis.lu/tc_workshop_prev.cfm

- the use of technology for sustainable manufacturing, and
- knowledge management practices to ensure effective supply integration.

Integration of manufacturing process techniques with biomaterials and micro- and nanotechnology to produce the next wave of high value products and production technologies is one of the conclusions (BMED, 2002). Linkage and connectedness will be most important attributes, (Cooper et al. 2006). Special emphasis is to be put on embedded information and communications technologies (ICT). It is seen to be crucial in the development of the knowledge based and networked enterprises involving manufacturing at nano-scales, the fusion of bio and engineering etc. Eu The network will be everywhere (enterprises, products and consumer), (Barbasi, 2005), and by diffusion of ICT, considerable performance leaps may be expected. Important features will be ambient intelligent technologies, mobile devices for collaboration, shared processes, databases, standards and integration architecture infrastructures.

Others see (CVMC, 1998.) driving technology spheres as
• adaptable, integrated equipment, processes, and systems that could be readily reconfigured; • manufacturing processes that minimized waste production and energy consumption; • innovative processes to design and manufacture new materials and components; biotechnology for manufacturing;
• system synthesis, modelling, and simulation for all manufacturing operations;
• technologies that could convert information into knowledge for effective decision making;
• product and process design methods that addressed a broad range of product requirements;
• enhanced human-machine interfaces;
• educational and training methods enabling the rapid assimilation of knowledge; and
• software for intelligent systems for collaboration.
as the most critical directions.

IMTI (IMTI, 2000) further suggests that manufacturers achieve higher levels of improvement by newly engineered materials, micro-electromechanical systems (MEMS), nanodevices, biological processing, and freeform fabrication techniques. There will be an increased utilization of unobtrusive networks of low-cost sensors in manufacturing control systems.

Enforced ICT applications, especially modelling and simulation (M&S), are envisioned as extremely important to commercial manufacturers' efforts that "quickly innovate, design, and produce the 'right product right' the first time" (BMED, 2002). Additional progresses are expected in the development of shared process, database, standards and architecture infrastructures, so M&S will be able to address modelling of products, manufacturing processes, and life-cycle performances that will permit simulation at various levels of resolution.

Significantly, technologically progressive companies are viewed in the context of a network of knowledge-based innovation relationships. The Integrated Manufacturing Technology Initiative (IMTI, 2000) highlights that all enterprise systems and processes will be interconnected seamlessly and draw on a deep base of science capturing experience to enable design, manufacture, and support of products with unprecedented speed, accuracy, and cost-effectiveness.

Emerging Collaborative Working Environments (CWE), making extensive use of telepresence, mobile AR etc., will offer a ubiquitous hardware and software infrastructure composed of resources providing a new blend of activity oriented, context-aware flexible software services supporting patterns of human interactions, human to machine interactions and collaborative gadgets, which all interact in a dynamic and pro-active fashion (Pallot et al. 2005). The collaboration intensity will go well beyond the states of context awareness between collaborating entities. This has massive restructuring of today's applications as a consequence and requires a re-visiting of current functionalities as well as product bundles (Boronowski et al.2005).

Furthermore future working environments may consist of hybrid spaces, composed of virtual and actual features. A hybrid virtual real environment is an optimal infrastructure for creative collaborative work. Visualisation of products/processes allows effective collaborative analysis of new ideas, experimenting to test different ideas, collaborative problem solving and distribution of tasks. Dependable mechanisms allow novel degrees of collaboration between all involved entities since it is reliable and provides an intelligent way to solve problems and to support humans to achieve goals. The key for success and dissemination is seen in the way that the features are provided (simple, focused and non-distracting, behavior models by agents). Increasingly mobile knowledge workers may be embedded in multiple team forms.

The synthesis of all predicted features results in a fast emerging networked manufacturing world. The ICT devices required for intensive participation (P&P) may become available for everyone on the globe (Figure 3). The efficient use however depends on high training and education levels. Based on these technological forecasts, several expert teams with research and company backgrounds studied selected interrelations.

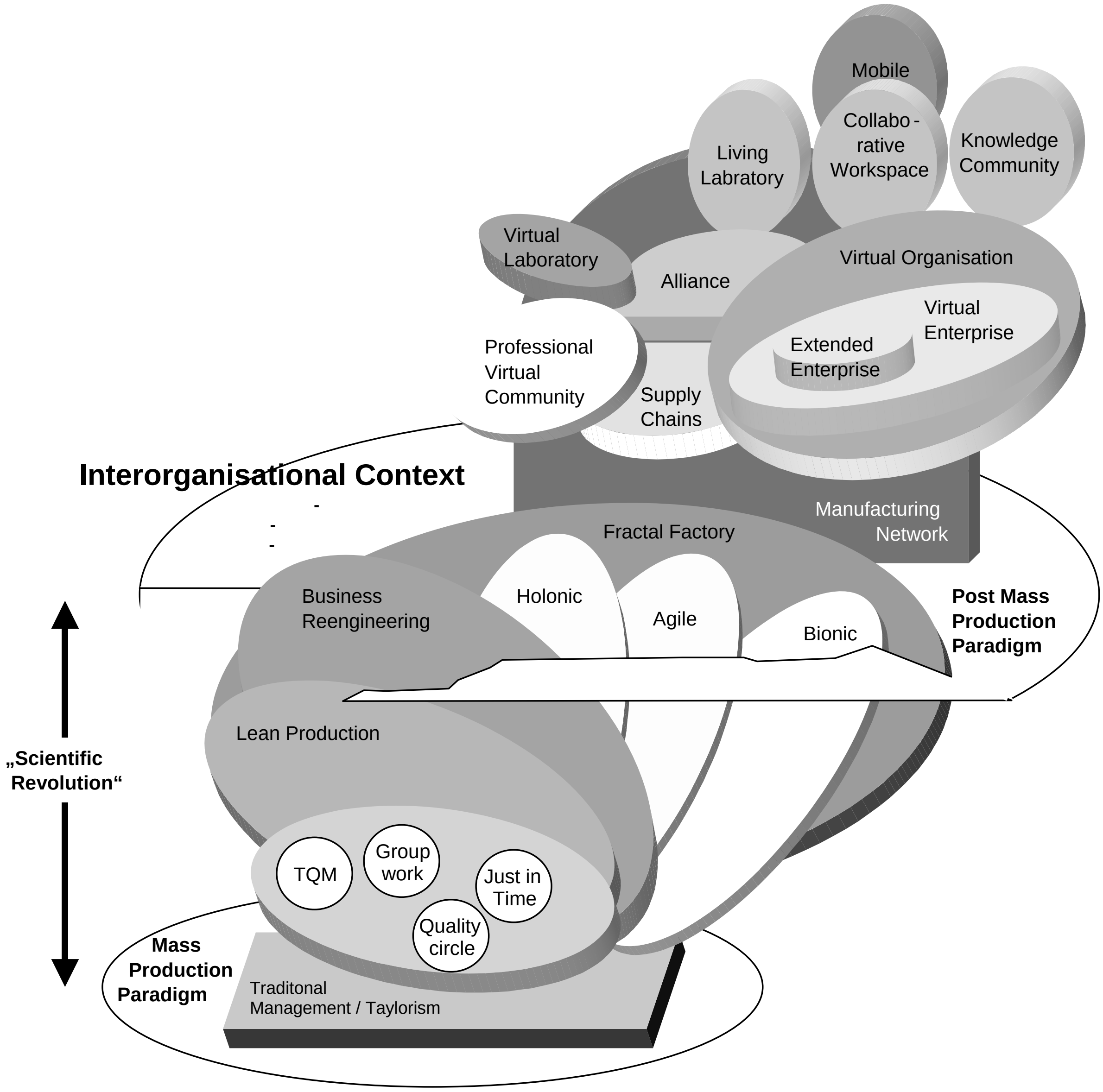

Figure 3: Production paradigm change trajectories unfolding important inter-organisational manufacturing philosophies and concepts

Global Manufacturing Structures – technology impacts on social drivers

-Results from Expert Group sessions-

Manufacturing is a means of satisfying higher societal objectives, and the current state of "making things" therefore has to be placed in a larger societal context (see also Committee on New Directions in Manufacturing 2004). Technology innovation causes more or less far reaching changes of individual and social life.

Trends toward differentiated forms of luxury; well being, safety, health and wellness will enforce. Deregulation and smart shopping consumers are manufacturing implications with good prospects for new, sustainable business models and good prospects for public acceptance of new technology.

Companies will increasingly use ICT to do manufacturing. Global structures will induce the demand for supra national regulations. The globally widening income gaps, enforced by value collisions and differences in legal rights interpretations could increase tensions calling for such regulations concerning manufacturing also.

Increasing competition calls for something like co-ordinated globalisation & global governance systems.

On the global scale manufacturing and the knowledge behind will be increasingly virtual/invisible and may therefore be suspected by groups in society to run "out of control". Manufacturing firms will have to accept much more transparency of and access to decision-making processes which directly affect their businesses. This will be a tremendous task of "navigation in politicised waters" where highest sensibilities for emerging risks become crucial capabilities. Manufacturing companies abilities on these sectors could force manufacturing to make enormous efforts (i.e. corporate governance, Tylecote, A. and Conesa, E., 1999) to maintain the social acceptance for their activities e.g. by engagements in public problem issues and its solutions. Enhancing credibility and trust in the sustainable use of the tremendous power of technological knowledge might become a major issue for future manufacturing companies.

By developing codes of conduct, companies are already interested to demonstrate their commitment to ethical principles, to comply with all relevant laws and regulations around the world and to show beyond doubt that such conduct is a fundamental part of their values and corporate culture. Moreover manufacturing companies will increasingly be expected to go beyond financial reporting and to manage and report the social and ethical impacts of their activities on the wider societies where they operate. Responsible business conduct will be beyond applicable laws and regulations. Industrial and other actors will need to accept that they are seen as responsible for various things that were traditionally regarded as externalities, and will need to account (in general terms) for these effects of their ameliorative actions (compare Miles et al, .2003). New policy networks need to be built that bridge the gaps that have resulted from the progressive dispersal of power, resources and knowledge throughout economies and societies. Fundamentally, future governance may be about making choices between the different and sometimes divergent ‘pillars’ of sustainability.

Local impacts of resources and social drivers

Technologies have the power to shape the values held by a society. The analysis of the relationships between resources and territory highlights the system effect created by the strengthened links between the economic, social, political and cultural actors sharing the same geographical space within a context of reticular interrelations constructed at the global level. There is a “place effect” which directs the action of actors. This effect is economic, political, social, cultural and ideological. It is this effect of place which leads to the structuring of local systems (functional clusters), as a result of the territorial arrangements and regional settings (see also Holbrook and Wolfe, 2002). If knowledge and resources concentrate in the same place, powerful poles may emerge, as technology will be attracted. High innovation dynamic in “Islands of Sustainability” with local competition offer excellent opportunities for local niches and lead markets for new technology, representing strong bases for high competitive global business (Fleury & Fleury 2006).

There will be dramatic changes in societies and work live. “Blurred industry carriers” characterize the ability of people to put highest priority on being able to be employed, becoming more and more attached to Professional Virtual Communities (PVCs) (Kakko et al. 2006), which may cause serious IPR protection problems for manufacturing companies. Producing high end knowledge will be frequently happen in such PVCs, the individuals orientation will be influenced by the territorial settings. In an ICT enabled functional region, the events will be more and more driven by entanglements between the networks of individuals inside and outside companies.

Collaboration will be expanded beyond the current concepts into complex organizations spontaneously emerging from dynamic versatile environments. Collaborative teams may turn the enterprises into densely interconnected networks. Use of powerful modelling and simulation systems supported by (ambient) VR/AR, will become an important manufacturing skill (SANTORO & BIFULCO, 2006). Again advanced ICT applications might build up major barriers for innovations in manufacturing. These barriers might be predominantly seen in the lack of general acceptance and the resulting social climate. In order to overcome these problems, much bigger efforts from governments (or sites, cites, NGOs) will be demanded that create positive impacts on social climate and regional cultures in general. Grow up of Living laboratories[3] and considerable efforts in dissemination etc. are possible effects. The availability of resources in combination with markets attracts technology even in fast cycles as the latest example of China demonstrates. Too fast developments may cause barriers by political systems or social forces, caused by resource consumptions and FDIs. New protectionism, initiated by influential citizen groups on regional level might become an issue, local level policy may interfere with manufacturing implications. Minimised resource consumption, less disposal, and less dependency on material and labour resources are challenges manufacturing is facing (compare also to the Gnosis successor MONOZUKURI now being announced as national Japanese manufacturing strategy).

Conclusion

Evaluating recent studies, developments and Delphi surveys on the field it is of high probability that the impacts of social drivers will be the most critical for the future of manufacturing. Based on world wide project efforts, applying Kuhn's theory of Scientific Revolutions on Post Mass Production Paradigms (PMPP), the paper draws main trajectories for future manufacturing by assuming strong interactions and cross impacts between the main drivers of the developments. The project methodology and the instruments and tools applied are sketched, important general results as well as specific examples are outlined. Globally, a manufacturing world of collaborative ICT is emerging. Ambient Intelligence and Connection of expertise, knowledge and creativity will be important features. Local and branch

[3] Living lab is a collaborative research methodology. The main emerging concept is the involvement of citizens in the innovation processes.

environments of Manufacturing Companies are embedded into these trends and may be detailed as well.

Ultimately the wider acceptance use of Information and Communication Technology seems to be the key to answer questions on how and how fast the developments will occur.

Acknowledgements

This work has been partly funded by the European Commission through the IMS Project *Gnosis*, the IST Project *Adrenalin* and the projects of the *AMI-Communities* as well as the Growth projects *Evolution II and TNEE.* The author wishes to acknowledge the Commission for their support. The author wishes to acknowledge his gratitude and appreciation to all the project partners for their contribution. BMBF funded the project *Stratema – Wachstum durch Wandlungsfähigkeit und produktnahe Dienstleistungen*, Land Sachsen-Anhalt funded the project *Verteiltes Produzieren.* The author wishes to acknowledge the Ministries for the support.

References

Anderson, C., Bunce, P. (2000), Next Generation Manufacturing Systems (NGMS), White Paper, CAM-I, Burleson, Texas

Barbasi, A-L., (2005), Network Theory—the Emergence of the Creative Enterprise- SCIENCE VOL 308

Bennett D J - Ed (1996), "Lean Production and Work Organisation", Special Issue of International Journal of Operations and Production Management, MCB University Press, Vol 16, No 2

BMED, (2002), Board on Manufacturing and Engineering Design, Division on Engineering and Physical Sciences, National Research Council, Modeling and Simulation in Manufacturing and Defense Acquisition: Pathways to Success, Washington D.C., USA, National Academic Press.

Boronowski, M., Herzog, O., Knackfuss, P., lawo, M. (2005), wearIT@work– Empowering the Mobile Worker by Wearable Computing – the first results, in: Pallot, M. & Pawar, K.S. (eds.), Proceedings of the 1st AMI@Work – Communities Forum Day, Nottingham

Brennan, R., Christensen, J., Gruver, W., Kotak, D., Norrie, D., Leeuwen, E. (2005), Holonic Manufacturing Systems – A Technical Overwiew, In R. Zurawski (Editor), The Industrial Information Technology Handbook, CRC Press, Industrial Electronics Series,

Camarinha-Matos, L. M., Afsarmanesh, H. (2005). "Collaborative Networks: a new scientific discipline", Journal of Intelligent Manufacturing, Vol. 16, No. pp. 439-452

Committee on New Directions in Manufacturing, (2004), New Directions in Manufacturing: Report of a Workshop, National Research Council, Washington DC, USA

Cooper, R., Evans, S., Gregory, S., O'Brien, C. (2006), "DESIGN-MAKE-SERVE, DELIVERING PRODUCTS AND SERVICES TO THE MODERN WORLD, Discussion document for the UK Manufacturing Professors Forum, July 2006, London

CVMC (1998); Visionary Manufacturing Challenges for 2020, (1998) () Committee on Visionary Manufacturing Challenges (CVMC), National Academy Press, Washington DC

Deen, S.M. (2003), Agent Based Manufacturing - Advances in the Holonic Approach, Advanced Information Processing, Berlin.

Dunning, J. H (1993) Multinational Enterprises and the Global Economy, Addison -Wesley, UK.

Fleury,A., Fleury, M. T. L.(2006) "UNDERSTANDING LATE-MOVERS IN INTERNATIONAL MANUFACTURING", 6th European Operations Management Association (EurOMA 2006), Glasgow, Scotland, Proceedings

Freeman, C, (1995), "The National System of Innovation"in historical perspective", Cambridge Journal of Economics 19

Gaines, B.R., D.H. Norrie and A.Z. Lapsley (1995),"Mediator: an Intelligent Information System Supporting the Virtual Manufacturing Enterprise" In Proc. of 1995 IEEE International Conference on Systems, Man and Cybernetics, New York,

GNOSIS (1994): "Intelligent Manufacturing Systems: IMS Test Case 7: Knowledge Science Institute and Division of Manufacturing Engineering", University of Calgary, Canada. ftp://ksi.cpsc.ucalgary.ca/IMS/GNOSIS/TC7.

Goldman, S. L.; Nagel, R. N.; Preiss, K.(1995), Agile Competitors and Virtual Organizations, New York, 1995

Holbrook J.A., Wolfe, D.A. (eds.) (2002), "Social Capital and Cluster Development in Learning Regions," in Knowledge, Clusters and Regional Innovation: Economic Development in Canada, Kingston: Queen's School of Policy Studies and McGill-Queen's University Press,

IMTI, (2000), - Integrated Manufacturing Technology Initiative - Integrated Manufacturing TechnologyRoadmapping Project - An Overview of the IMTR Roadmaps, London, Ontario, Canada

Kakko, I., Lavikainen, M., Glotova, T., “NETWORK OASIS: NEW PRACTICES FOR EMERGENT COLLABORATIVE WORKING ENVIRONMENTS, 7th IFIP Working Conference on VIRTUAL ENTERPRISES Helsinki, FINLAND 25-27 September 2006

Kidd, P.T. (1994), Agile Manufacturing: Forgoing New Frontiers, Addison –Wesley

Kuhn, Th. S. (1962): The Structure of Scientific Revolutions, Chicago

Kühnle, H.,(1995), “L'entreprise fractale”, In: Braesch, C. (Hrsg.); Haurat, A. (Eds.) 1995, “La modélisation systémique en entreprise”, Pôle productique Rhône-Alpes. Paris

Kühnle, H.; Martinetz, J.(2000) Paradigmatic Options for Future Production. In. IMS / GNOSIS Consortium: GNOSIS Open Day Conference (Tokyo March 6th 2000) -Proceedings

Kühnle, H.; Schmelzer, S.F, (1995), A NEW PARADIGM - THE FRACTAL VIEW OF THE FACTORY, The Individual in the Focus of the Factory. In: British Academy of Management - Annual Conference 1995 (Sheffield, UK September 11th –13th 1995) - Proceedings

Liker, J. (2003), The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer, First edition, McGraw-Hill, , ISBN 0071392319.

Lundvall, B.-A, (1988), Innovation as an interactive process; from user-producer interaction to the national system of innovation. In Dosi, G. Freeman, C., Nelson, R., Silverberg, G. and L. Soete (eds.) Technical Change and Economic Theory, New York, Pinter, pp. 349- 369.

Miles, I., Weber, M., Flanagan, K. (2003), THE FUTURE OF MANUFACTURING IN EUROPE 2015-2020 THE CHALLENGE FOR SUSTAINABILITY Governance, Social Attitudes and Politics, Futman, Final Report

NGM (1997), Next-Generation Manufacturing: A Framework for Action. NGMS Project Office, Bethlehem, Pennsylvania, USA http://www.agilityforum.org

Ohno, T. (1988), Toyota Production System: Beyond Large-Scale Production, Productivity Press

Okino, N. (1993), Bionic Manufacturing Systems, Conference on Flexible Manufacturing Systems, Past, Present-Future (Ed: J. Peklenik), Ljubljana: Faculty of Mechanical Engineering

Pallot, M., Prinz, W., Schaffers, H.(2005), Future Workplaces, towards the “Collaborative” Web, in: Pallot, M. & Pawar, K.S. (eds.), Proceedings of the 1st AMI@Work – Communities Forum Day, Nottingham

SANTORO, R., BIFULCO (2006), A., The “Concurrent Innovation” paradigm for Integrated Product/Service Development, ESoCE-NET White Paper, http://www.ESOCE.net

Shapira, P., Youtie, J.,Urmanbetova, A. (2004), Advanced Technology and the Future of U.S. Manufacturing Proceedings of a Georgia Tech research and policy workshop, Georgia Institute of Technology, Atlanta, USA

Tomiyama, T. (1997), “A Manufacturing Paradigm Toward the 21st Century,” Integrated Computer Aided Engineering, Vol. 4, No. 3,

Tylecote, A. and Conesa, E. (1999) “Corporate Governance, Innovation System and Industrial Performance”, Industry and Innovation 6, 1,

VanBrussels, H., Wyns, J., Valckenaers, P., Bongaerts, L., Peeters, P.(1998) Reference architecture for holonic manufacturing systems - PROSA, Computers in Industry 37,

Webb, C., Wunram, M., Lettice, F., Klein, P., (2005), Improving Problem Solving Capabilities in Concurrent Engineering via Knowledge Transformation & Six Complexity Science Principles, in In: Proceedings of the 11th International conference on concurrent enterprising - Integrated engineering of products, services and organisations, Nottingham, pp. 111-118

Womack, J.; Jones, D.; Roos, D. (1990), The Machine that changed the world, New York, USA