An approach to the Integrated Design and Development of Manufacturing Systems

H. Nylund[1], K. Salminen[2], P.H. Andersson[3]
[1,2,3]Department of Production Engineering, Tampere University of Technology, P.O. Box 589, FI – 33101
Tampere, Finland
hasse.nylund@tut.fi

Abstract
This paper describes an approach to integrated manufacturing systems. It aims to integrate design and development activities, as well as the entities existing in a manufacturing system. A model of manufacturing systems is presented, including manufacturing entities with different roles and domains related to them. The characteristics of the manufacturing entities are discussed, including changeability, service orientation, and learning capabilities. One of the main enablers is a digital manufacturing system, which includes tools for modeling, simulation and analysis, as well as digital information and knowledge. This is illustrated by an example process, from product ideas to the efficient production of the products.

Keywords:
Manufacturing System, Integration, Design, Development

1 INTRODUCTION

The competition in global markets obliges manufacturing enterprises to respond rapidly and in a cost-efficient manner to changing constraints and requirements. The enterprises are required to be context-aware and to have knowledge about their skills and capabilities. They have to be able to adapt to, for example, changing possibilities existing within the industrial environment, requirements derived from customer demands, and constraints limiting how they can do business. An integrated environment, connecting the manufacturing activities, can be one of the main enablers for successful operation in the markets. The integration of (a) design and development activities and (b) products and production systems into one system enables existing skills and knowledge to be used more efficiently. It can offer a wide knowledge and information base to be used in decision-making processes. This paper describes an approach to such integrated manufacturing systems. It is part of an ongoing scientific research project, FMS 2010. The objective is to improve the efficiency of manufacturing enterprises by offering capabilities which can support all activities, from visions and ideas to actions and customer satisfaction.

A model of integrated manufacturing systems is presented. It consists of manufacturing entities of products, resources, and orders which have different roles in the manufacturing system. The entities are connected through the process, production, and business domains. The entities are explained with their internal structure consisting of digital, virtual, and real parts as being autonomous and their communication part as being involved in co-operation between different entities. The entities are also examined in a context ranging from industrial ecosystems to individual entities. The changing characteristics of the system are discussed from the viewpoints of changeable, learning, and service-oriented systems and entities. This can lead to a knowledge-based manufacturing system in which the information and knowledge are also constantly changing. A digitally presented manufacturing system is one of the key enablers in the changing environment to keep the information and knowledge up-to-date and available.

2 THE FMS 2010 CONCEPT OF ADAPTIVE MANUFACTURING SYSTEMS

The aim of the FMS 2010 research project is to create a concept of adaptive and autonomous manufacturing systems. The intention is to integrate the design and development of products, production systems, and business processes into one environment. The entities of the system can exist in a distributed network both on the physical and information levels. This provides more effective use of existing knowledge and skills. Duplicate design and development processes can be reduced and more cost-effective solutions achieved.

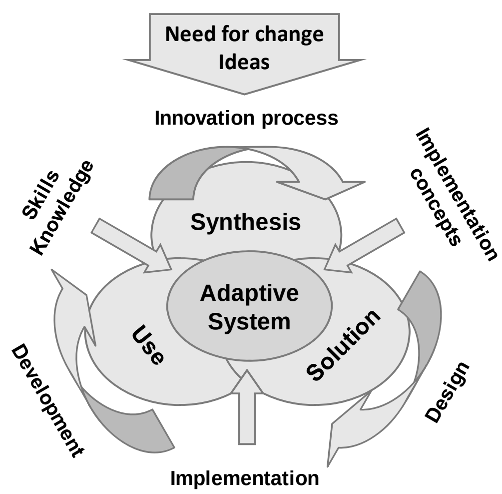

Figure 1: The process of the FMS 2010 concept [1].

Figure 1 illustrates the process of the FMS 2010 concept. The process combines three main phases: synthesis, solution creation, and the use of the system created. The phases are connected with processes of emergence as implementation concepts, the implementation of the new system, and the growth of skills and knowledge as the system is operating. In the synthesis phase, the existing skills and knowledge of a manufacturing system are combined with new requirements and possibilities, derived from ideas and needs for change. In the process of creating the implementation concepts, the solution principles are used to create the solution. In the event of contradictory situations, the different goals are analyzed, using the principle of positive intention [2]. This is done to achieve a mutually acceptable solution that can be considered for implementation. When the newly implemented system is in operation, it is constantly developed. The knowledge and skills of the manufacturing system are updated. During each of the phases, accepted principles will be added to the existing skills and knowledge and they will form the basis for how future design and development challenges are met.

The process is iterative both at the whole process level and also in the steps of the process. For example, a synthesis can be repeated until acceptable solution alternatives are found. In a similar fashion, a whole loop can be repeated to achieve a feasible solution.

The approach utilizes, to the appropriate extent, principles from the paradigms of Holonic Manufacturing Systems (HMS), Fractal Manufacturing Systems (FrMS), Bionic/Biological Manufacturing Systems (BMS), Cognitive Technology Systems (CTS), and Service-Oriented Architecture (SOA). Table 1 summarizes the main principles used.

Principle	A short description
HMS [3][4][5]	Autonomous and co-operative entities. Network-based teams. Modular system structure.
FrMS [6]	Horizontal and vertical self-similarity on all structuring levels.
BMS [7]	Evolving capabilities. New methods and methods integration . Intelligent and adaptive structures.
CTS [8]	Developing reasoning capabilities. Adaptive decision-making.
SOA [9]	Formal communication language and content between the entities.

Table 1 : A brief summary of the main principles used in the FMS 2010 approach.

The process of the FMS 2010 concept is being piloted in several major Finnish enterprises. Each of them has its specific challenges, which differ from each other and give an individual aspect to developing the concept on a detailed level. The FMS 2010 research project is divided into work packages of:

- Challenges in state-of-the-art manufacturing systems technology.
- Manufacturing systems control architecture.
- Integration of manufacturing methods.
- Flexible automated fixtures.
- Modeling, simulation, and analysis of machine tools and robots, as well as manufacturing systems.

3 MODEL OF INTEGRATED MANUFACTURING SYSTEMS

The model of integrated manufacturing systems to be described is intended as a starting point for modeling real manufacturing systems. The basis of the model is derived from the principles behind the term '*holon*'. It comes from the Greek word '*holos*', which is a whole, and the suffix '–*on*', meaning a part. Therefore the term holon means something that is at the same time a whole and a part of some greater whole [10].

The model of integrated manufacturing systems consists of manufacturing system entities and related domains, the structure of individual manufacturing entities, and the structuring levels of the entities. A manufacturing system is, at the same time, part of a bigger system and a system consisting of entities.

3.1 Manufacturing System Entities and their Related Domains

The model of manufacturing systems explains the system with manufacturing entities and their related domains; see Figure 2. The basic entities are products, resources, and orders, based on the reference architecture of HMS: the Product-Resource-Order-Staff architecture (PROSA) [3][4]. The entities are connected with the domains of process, production, and business. Each part of the manufacturing system has a specific role, and all of them have to be considered in an integrated environment for successful operation.

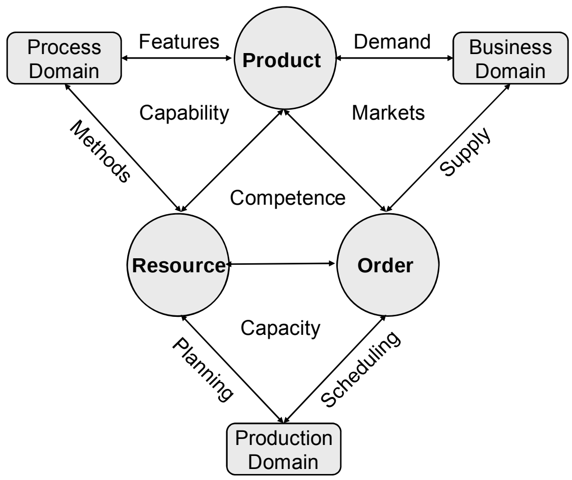

Figure 2: The manufacturing system entities and their related domains, adapted from [11].

Products are what the manufacturing system is offering to its customers. *Orders* are instances of products the customers are purchasing. The customers can be other entities within the same enterprise, or entities in the enterprise network. The ordered products will be manufactured with the *resources* existing in the manufacturing system.

The business domain connects products and orders. In the markets where a manufacturing system exists, the demand of customers has to be met with sufficient supply. In *the process domain*, the capability to manufacture the products is defined. The system needs to be able to manufacture all of the features of the products, i.e. the resources should be associated with corresponding methods. The resources, having the needed capabilities, also define the capacity of the system in *the production domain*. It is responsible for manufacturing orders at the right time. It should have enough capacity to manufacture the volume and scalability needed to handle any variation in orders. The competence of a manufacturing system is defined by the skills needed in each of the different types of entities and their related domains. Each of them has to be efficient in order to achieve feasible and efficient results.

3.2 Structure of System Entities

The entities, despite having different roles, have similar internal structures. The structure consists of digital, real, and virtual parts explaining the autonomous part of the entities. The entities are connected via the communication part, which makes possible co-operation with other entities existing in the system.

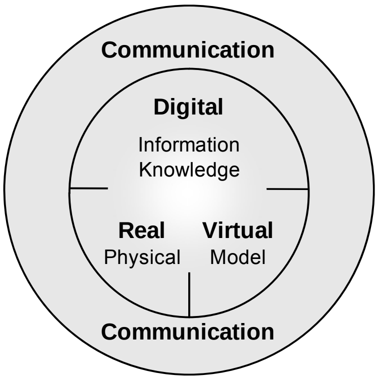

Figure 3: Structure of manufacturing entities [11].

The digital part includes all the digitally presented information and knowledge. It is used for developing and controlling the real system, as well as building the virtual models. *The real part* represents what exists physically in the real system, such as machines and tools, humans, and products to be manufactured. *The virtual part* is a representation of the physical part as a computer model. This includes, for example, CAD models of products and production facilities and simulation models of robots, machine tools, and manufacturing systems. *The communications part* is responsible for the co-operation on the physical and information levels. The information part of the communication is the language and content of the data that are transferred within the system. The amount of information transferred between the system entities is kept to a minimum in order to reduce the complexity of the operations.

In the context of a currently operating manufacturing system, the information for the real and virtual parts is the same as that existing in the digital part. New information and knowledge, gathered from either the real or virtual worlds, is added to the digital part and made available for both. In future design and development cases, a copy of the digital part is used to avoid inaccurate information being added to the current system. This is done to eliminate false information from failed ideas for future design and development cases.

3.3 Horizontal and Vertical Self-Similarity

As a manufacturing system is a part of some larger system and at the same time consists of subsystems, it can be examined on different vertical structuring levels. A manufacturing system is also a part of a supply chain, which is its horizontal context. Material comes from a supplier and is delivered to a customer. Figure 4 presents the structuring levels of different industrial entities, where a manufacturing system is part of a bigger entity and at the same time consists of several entities on lower structuring levels. At the top level it is an industrial ecosystem, where all the entities of lower levels exist. Being aware of the changes in the ecosystem enables a more rapid response to be made when new partners, suppliers, or customers are required.

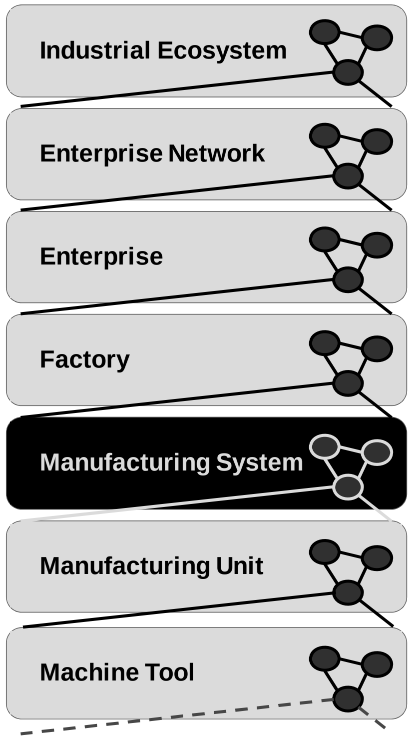

Figure 4: The structuring levels from industrial ecosystem to machine tools.

A manufacturing system entity consists of manufacturing unit entities, i.e. it is a network of resources needed to manufacture all the features of product entities. It also has resources for storing and handling material and transferring it between manufacturing units. The product entities are typically part families from which the volume and variation of orders is composed.

Manufacturing units consist of resource entities of machines, devices, workers, and other entities required, such as robots, fixtures, sensors, readers etc. The units are designated to manufacture certain product entities, i.e. work pieces that have similarities in size, shape, features, material properties etc. They are also required to produce a certain amount of order entities to keep the material flowing between manufacturing units.

A factory entity consists of manufacturing and assembly systems, as well as storage areas for blank parts and final products, including both manufacturing and assembly units. The products are typically final products and the customers are the final users of the products. Enterprises and enterprise networks consist of factory units, which can exist globally. The distance between the entities brings logistics into the picture as an important factor. The difference between enterprises and their networks is that entities in the network may have different owners and possibly contradictory goals.

The behavior on the industrial ecosystem level differs from the five lower structuring levels because it is not under any administration. A manufacturing enterprise can have a certain amount of control over its own enterprise network, but it cannot control other entities in/outside or coming into the ecosystem.

A level above includes all the structuring levels below it. The levels are self-similar externally in terms of the structure of the entities as they communicate in the same environment. Despite their self-similarity, internally their autonomy can vary and they can be different from each other, even when they have a similar role in the system.

From another viewpoint, manufacturing entities can be similar or different, depending on who they are examined by. A product in a manufacturing system is a resource from the customer's viewpoint. Similarly, the resources in a manufacturing system are products from the viewpoint of resource suppliers.

4 CHANGING CHARACTERISTICS

Manufacturing systems operate in a constantly changing environment. The changes can be external or internal, direct or indirect. Typical external and indirect sources for change are politics, society, ethics, the world economy, and the environment [12]. Laws and different rules are examples of external and direct sources for change. These sources can be mandatory or voluntary. Mandatory sources force the manufacturing system to adapt to the changes. For those changes that are voluntary, the manufacturing system has to choose whether to change or not.

The decisions will have an impact on the competence of the manufacturing system. Customers, partners, and suppliers are external and direct sources for change from the viewpoint of a manufacturing system. They differ from the other external and direct sources in their nature, as they are similar entities communicating in the same environment as the manufacturing system. Similarly, new ideas, materials, and technologies can derive from the manufacturing system itself or from the context.

The external changes will cause internal changes that will change the system. The changes can affect the system entities of products, resources, or orders, as well as their related domains of business, process, and production. A change within a system will almost always cause a chain of change events until the system has adapted to the new situation.

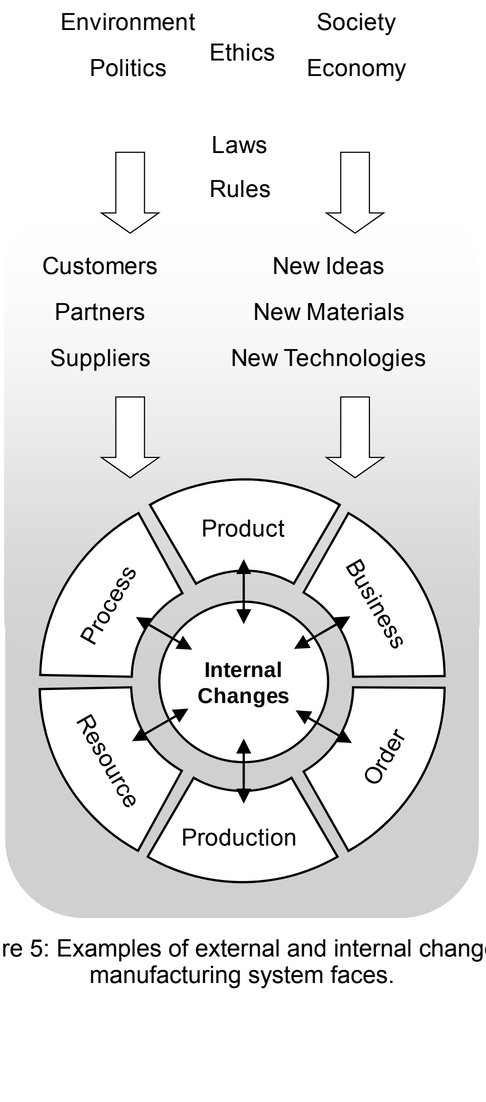

Figure 5: Examples of external and internal changes a manufacturing system faces.

4.1 Service-Oriented and Learning Manufacturing Entities

The basic conceptual model of SOA architecture consists of service providers, service requesters, and service brokers [9]. The entities in a digital manufacturing system based on SOA have the following roles:

- *Service provider entities* are typically the resource entities having the needed capabilities.
- *Service requester entities*: the order holons. The resource entities can also be in the role of a requester, for example when they require maintenance services.
- *Service broker entities* can be seen as rules of the co-operation between the entities, i.e. the autonomy of the upper level of entities.

In the proposed model of manufacturing systems having the basic building blocks, products, resources, and orders, services happen in the domains of process, production, and business. Knowledge-based services can be seen in three dimensions: role, context, and receipt. They are based on the distributed character of knowledge: normative expectations, interactive situations, and dispositions [13] and object, cognitive state, and capability [2]. Each entity has a role in the system in which it exists, i.e. it has expectations of the other entities. It is also one of the objects existing in the system. In the context an entity is performing its activities as interactive situations where the cognitive state of the entity collects data and information. The dimension of dispositions is seen as a receipt, data and information collected from the system, to learn and improve the knowledge as the capability of the entity.

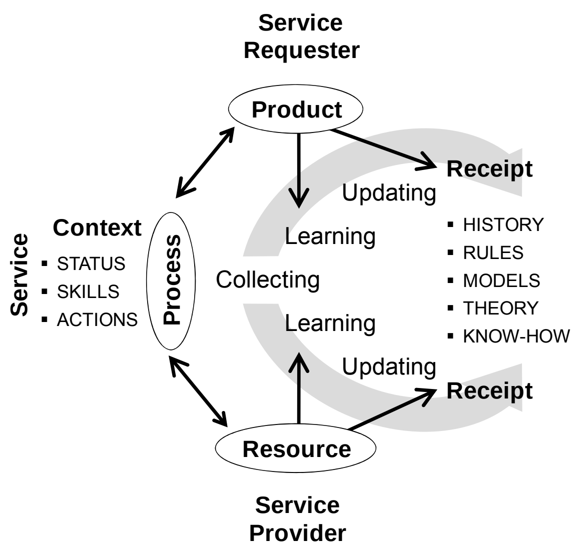

Figure 6: Roles, context, and receipt of products and resources.

Figure 6 presents an example service happening in a process domain between a product and a resource. The resource entity is providing a service as requested by the product entity. The service is a manufacturing process happening in a certain context. The actions during the service depend on the skills of the resource entity and the state of the system. When the service is in operation, both resource and product entities collect data from the process. They learn and update the data and information they receive. When a certain product entity uses a service provided by a certain resource entity, the data collecting, learning, and updating phases include adding the same data and information to the knowledge of both entities'.

The knowledge of a resource entity is updated with several product entities using the services it provides. In a similar fashion, the knowledge of a product entity consists of all the services it requests.

4.2 Changeable Manufacturing Systems and Entities

The changeability of manufacturing systems and entities can be classified into changing by requirements, changing by learning, and changing structure during the lifecycle of the entity. The entities face changing requirements during their lifecycles. Typically, the entities must change during their existence both to meet the new requirements and to improve their actions.

Changing by requirements

An entity may have to change because its requirements change. The need for change can be seen from the vertical structuring levels:

- *Industrial ecosystem* - Being aware of existing and future possibilities and requirements.
- *Enterprise network* - To rapidly form a new enterprise network structure when markets change.
- *Enterprise* - Transparent co-operation with suppliers, partners, and customers to get better results.
- *Factory* - Rapid response to changing product families.
- *Manufacturing system* - Flexibility to change manufacturing processes with minimal reconfiguration.
- *Manufacturing unit* - To rapidly change the system configuration for the requirements of new part families.
- *Machine tool* - Ability to change between work pieces with minimal setup times.

Changing by learning

Changing by learning can be understood as the evolution of skills and knowledge from unknown towards core skills and knowledge; see Figure 7. An unknown activity cannot be considered until the possibilities are known. It requires new information and knowledge to be acquired from the enterprise network or industrial ecosystem. When it is clear that the change is possible, the technologies needed can be investigated. By having a wide network of knowledge, it is possible to gather information on the technologies, skills, and knowledge existing in the enterprise network. When the technologies are available, the system may be configured and the capabilities achieved. When the actual possibility is implemented and integrated into the system, the capability exists in the system. As the system operates, the capabilities are constantly improved towards core information and knowledge by learning from actions.

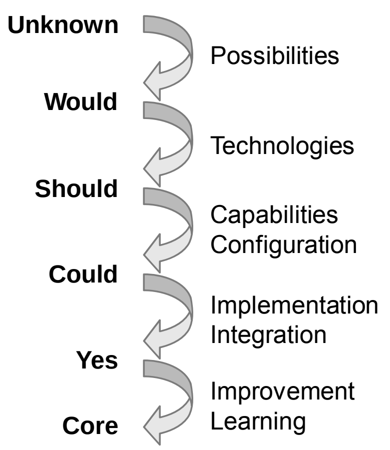

Figure 7: A change from unknown to core knowledge.

Changing structure during life cycle

The structure of a manufacturing entity consisting of digital, virtual, and real parts will change during the life cycle of the manufacturing entity. Not all of the parts have to exist all the time. A product entity, in the early phases of the design process, is an idea, a vision of what it could be, and has only a vague description that can be presented digitally. When the design evolves into a detailed solution principle, there could be a virtual part, a computer model that can be used to test the functionality and present the product idea to other people. The physical part exists for the first time if prototypes are manufactured. When the product entity is accepted into production, instances of product entities, the order entities, are realized. They can have the physical product and also digital information and virtual models of the product as parts of the service to a customer.

From past via present to future

One viewpoint from which to consider digital manufacturing systems is the time span in which the entities exist. It can be seen, for example, as past, present, and future.

The past exists as data and information collected from the manufacturing system. As the system operates, the events occurring in the manufacturing system are logged. The data can be examined and analyzed to find out what happened and why it happened. In finding the root causes for the phenomena, the system can learn from its actions. It can improve the manufacturing processes, update its skills and knowledge, and be prepared for unexpected situations in the future.

At the present, during the current operation of the manufacturing system, the digital and real manufacturing systems co-exist, constantly updating each other. The state of the real manufacturing system can be seen in the digital manufacturing system and vice versa. Actions can be taken on the basis of the state of the system as a starting point.

The viewpoint of the future can be divided into tactical decisions and visions, the difference being the time horizon. In both cases, the operating process occurs mostly in the digital manufacturing system because the events under investigation have not happened yet. Tactical decisions consider the near future into which the manufacturing system is heading. Future visions are similar to tactical decisions, the difference being the time horizon. The outcome of future visions is more obscure but there are more possibilities for creativity and idea investigations.

4.3 Knowledge-Based Manufacturing System

In a changing environment, managing the information and knowledge of a manufacturing system is an important factor. A manufacturing system can be characterized as a distributed knowledge system [13] and managing knowledge as a dynamic and continuous organizational phenomenon [14].

Knowledge can be divided into explicit and tacit knowledge [15]. Explicit knowledge can be presented as symbols, i.e. it is possible to represent it formally and digitally. Tacit knowledge consists of, for example, human beliefs, know-how, and skills. Managing the two dimensions of knowledge includes processes of knowledge creation, knowledge storage and retrieval, knowledge transfer, and knowledge application [2].

A service-oriented manufacturing system, presented digitally, can enable information and knowledge to be managed. The intelligence of the manufacturing entities is kept as their autonomy. Only the needed information is transferred between the co-operating manufacturing entities. This requires a formal communication language and information content. If all the entities can communicate formally, the entities can be changed, added, or removed without changing the system itself. Each entity can exist in the system regardless of their autonomous part. This enables different types of manufacturing entities to be integrated into one system.

5 DIGITAL MODEL OF MANUFACTURING SYSTEMS FOR THE INTEGRATED APPROACH

A Digital Manufacturing System is one of the main enablers of efficient design and development processes. Presenting the information and knowledge of manufacturing systems digitally makes possible a wider outlook on all aspects of manufacturing systems, compared to the skills and knowledge of individual humans. It can be used to evaluate everything from creative ideas during conceptual stages to detailed solution alternatives.

Research on Digital Manufacturing on different levels, from enterprises to manufacturing entities, has no commonly agreed definitions, but they all share similar characteristics (see, for example: [16][17][18][19][20][21]):

- An integrated approach to improve product and production engineering processes and technology.
- A framework for new technologies, including the collection of systems and methods.
- Computer-aided tools, such as modeling and simulation, for planning and analyzing real manufacturing processes.

In this paper, the Digital Manufacturing System is defined as "*An integrated environment for the design and development of products, production systems, and business processes*" [11]. The digital manufacturing system includes modeling, simulation, and analysis by using computer tools, as well as digitally presented information and knowledge. It exists only once in a formal and up-to-date form. It can be distributed, but is accessible to all parties regardless of time and location.

5.1 Modeling, Simulation, and Analysis

Modeling in a wide sense is used to understand something better, why the system behaves in the way it does. It can be used to repeat or refine performance to achieve a specific result, as well as to extract and formalize a process in order to apply it to a different content or context [22].

Simulation, especially discrete-event simulation (DES), is used when the model evolves over time. The states of the manufacturing entities change at separate points in time. Simple models can be investigated analytically, but typical manufacturing systems and the relations between the entities are too complex to solve without simulation [23]. The use of modeling and simulation is one of the largest application areas of the design and development of manufacturing systems. Typical areas usually addressed using modeling and simulation are, for example [24]:

- Need and the number of resources, both human and machines, i.e. defining the needed capacity of the system.
- Performance evaluation, such as throughput and bottleneck analysis.
- Evaluation of operational procedures, such as planning, controlling and scheduling of manufacturing activities.

In an integrated design and development environment, the modeling and simulation of manufacturing systems is a part of the digital manufacturing system. It needs to be kept up to date, rather than a typical simulation model that is created in a project and then, after analysis of the results, becomes obsolete or is only seldom updated.

5.2 An Example from Product Ideas to Efficient Solutions

Requirements from customers, needs for change, and general requirements combined with ideas turn into solution principles. Further on in the process, the solution principles translate to solution alternatives, which define the manufacturing requirements. Figure 8 presents an example process from the requirements towards an efficient solution to meet customer demands. It includes the verification and validation of manufacturing capabilities and the capacity to manufacture the new product. The three loops in the process are the product requirements loop, capability loop, and capacity loop.

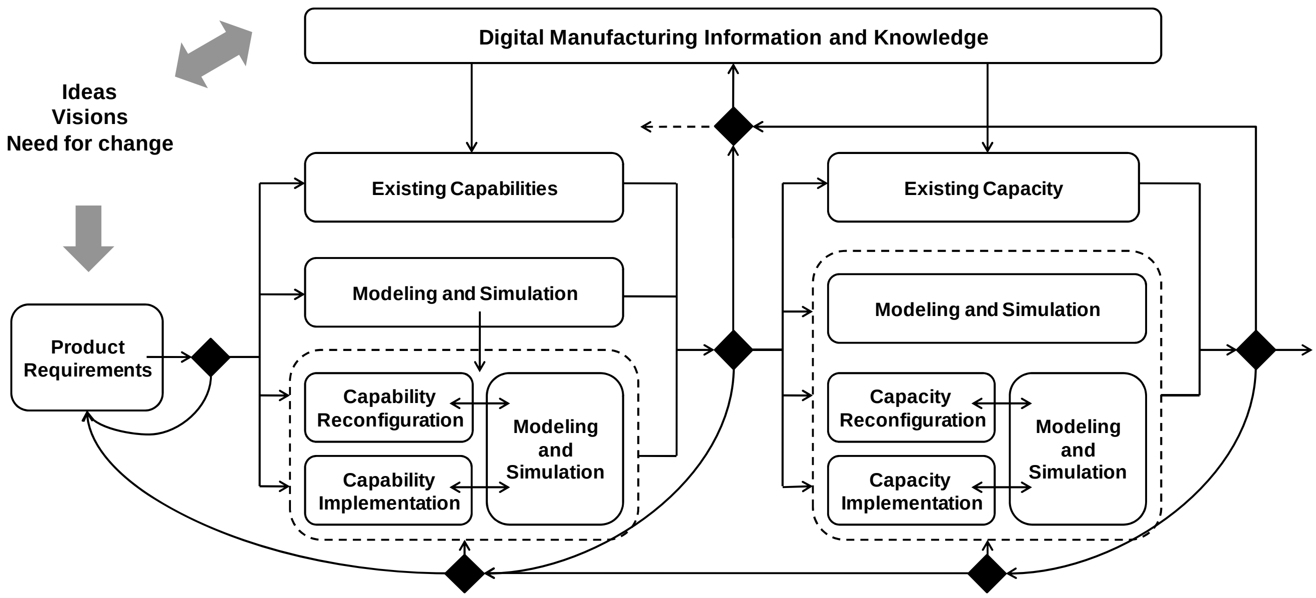

Figure 8: An example of the integrated approach from product ideas to deliverable products and services.

The product is divided into features which form the service requests, the requirements for the system. For each requirement there must exist a corresponding capability, a method to manufacture the product. The resource having this capacity is the service provider. The first decision is made in the product requirements loop, where it is decided if the product design alternative is worth going on with. It is possible to go back and modify the design or to check if there are capabilities. In the capability loop the result between each of the requirements and capabilities can be classified, for example, as one of the following five categories:

- *Existing capabilities*: The capabilities exist for all of the product requirements without any need for changes to the system. The products can be manufactured as the service requests have service providers.
- *Possible existing capabilities*: At least some of the product requirements need further investigation as to whether the capabilities exist. The requirements are close to the existing capabilities and, using modeling and simulation, the capabilities can be verified.
- *Capabilities after reconfiguration*: There is no existing capability but it may be possible to reconfigure the system so that it has the capabilities. By modeling the reconfigured system the possibility can be verified.
- *Capabilities after implementation*: The system does not have the needed capability. It may be possible if new capabilities are added to the system. Again this can be verified using modeling and simulation.
- *No capability*: The result may also be that there are no capabilities and they cannot be implemented either. This leads to the need for an alternative solution, which leads to a result that fits into one of the first four categories.

When it is known that the capabilities exist for all the product requirements, the efficiency of the capabilities still needs to be evaluated against factors such as cost, quality, and time. It has to be decided if the solution alternative is good enough. It can be further investigated in the capacity loop or it can be rejected and sent back to the capability loop.

If all the needed capabilities exist, the capacity of the system has to be checked. The same five categories can be used in capacity evaluation. If it is known that there is enough capacity, nothing else has to be done. Modeling and simulation can be used to verify that there is enough capacity. It can also be used in capacity reconfiguration and implementation issues. Modeling and simulation of capacity has the same constraints as in the case of capabilities. The capacity for existing volume and variation still has to exist when new products are considered as an addition to existing products. In the capacity loop, the solution can be accepted or rejected, as in the capability loop. If the solution is rejected, it can be sent back to the capability loop or further back into the design requirements loop.

All the solutions are the results of decisions which combine existing digital information with the new requirements and possibilities. The digital information and knowledge is input as it is used as support for decisions when existing knowledge is combined with new knowledge gathered by the new product requirements. It is also output from the solutions, as the system is updated to include the new information and knowledge.

5.3 Benefits and Challenges of Digital Manufacturing Systems

Both digitally presented information and knowledge and the computer tools for modeling, simulation, and analysis offer efficient ways to achieve solutions for design and development activities. General benefits include, for example:

- Experiments in a digital manufacturing system, on a computer model, do not disturb the real manufacturing system, as new policies, operating procedures, methods etc. can be experimented with and evaluated in advance.
- Solution alternatives and operational rules can be compared within the system constraints. Possible problems can be identified and diagnosed before actions are taken in the real system.
- Modeling and simulation tools offer real-looking 3D models and animations that can be used to demonstrate plans and train workers.
- Being involved in the construction of the digital manufacturing system tasks increases individuals' knowledge of the system. The experts in a manufacturing enterprise acquire a wider outlook compared to their special domain of knowledge.

More specific advantages related to the integrated approach of manufacturing systems from product ideas to deliverable products and services and presented in Figure 8 are, for example:

- When new products are introduced, service requests can be simulated and they provide a response in terms of the system's capability to manufacture the products.
- If changes are needed, different solution alternatives can be simulated, analyzed, and compared. The most suitable solution can be selected to be considered for implementation.
- The solutions can be viewed against factors such as cost, quality, and time, as well as how they affect the operation of the existing system.
- Using the approach in the early steps of product requirement analysis makes it possible to detect change requirements in advance.

Challenges exist both in the autonomous and co-operating parts of the digitally presented manufacturing entities. The internal part has to include only the needed information and knowledge and it also has to improve the actions taken by individuals with their own personal skills. The entities co-operating with other entities need to have predefined ways to communicate. Both the language and content of the transferred information and knowledge have to be formally described in such a way that both humans and machines can communicate in the same system.

6 CONCLUSIONS

Changeability is a precondition for success. It is a combination of creativity with quality and productivity [25]. An approach to manufacturing systems that integrates product, production, and business processes is an enabler for the efficient use of design and development activities. The model of the integrated system, with manufacturing entities with different roles and self-similar structures, as well as their relations, makes it possible to construct models of real manufacturing systems. The model supports the changing characteristics of manufacturing systems by updating the information and knowledge when the system changes, for example by learning from its actions and by adapting to new requirements. If the system is presented digitally, the information and knowledge of the system can be presented formally and it is available to all relevant parties, regardless of time and location. Different solution alternatives can be examined and results can be achieved before they are put into practice in the real system. The consequences of changes in one area can be evaluated and it is possible to see how they change other areas and the whole system.

7 ACKNOWLEDGMENTS

This paper is part of a scientific research project, FMS 2010. It is co-financed by Tekes, the Finnish Funding Agency for Technology and Innovation, and several major companies in Finland.

8 REFERENCES

[1] Nylund, H., 2008, Changeability issues in adaptive manufacturing systems, Flexible Automation and Intelligent Manufacturing, FAIM2008, Skövde, Sweden, 30 June – 2 July: 1037-1044

[2] Dilts, R., 1998, The Principle of 'Positive Intention', Robert Dilts NLP Home Page, Retrieved: 15th July 2008, http://www.nlpu.com/Patterns/pattern2.htm

[3] Wyns, J., 1999, Architecture for Holonic Manufacturing Systems - The Key to Support Evolution and Reconfiguration, PhD thesis, K.U. Leuven, Belgium

[4] Van Brussel, H., Wyns, J., Valckenaers, P., Bongaerts, L. and Peeters P., 1998, Reference architecture for holonic manufacturing systems: PROSA, Computers in Industry, 37: 255-274

[5] Valckenaers, P., Van Brussel, H., Bongaerts, L. and Wyns J., 1994, Results of the Holonic Control System Benchmark at the K.U. Leuven, Proceedings of the CIMAT Conference, Troy, NY, USA, 128-133

[6] Warnecke, H.J., 1993, The Fractal Company: A Revolution in Corporate Culture, Springer-Verlag, Berlin, Germany

[7] Ueda, K., Vaario, J. and Ohkura, K., 1997, Modelling of Biological Manufacturing Systems for Dynamic Reconfiguration, Annals of the CIRP, 46/1: 343-346

[8] Zäh, M.F., Lau, C., Wiesbeck, M., Ostgathe, M. and Vogl, M., 2007, Towards the Cognitive Factory (Keynote Paper), Proceedings of the 2nd International Conference on Changeable, Agile, Reconfigurable and Virtual Production, Toronto, Canada, July 22-24: 2-16

[9] W3C, 2004, Web Services Architecture, http://www.w3.org/TR/ws-arch/, accessed 18th July 2008

[10] Koestler, A., 1989, The Ghost in the Machine, Arkana Books, London

[11] Nylund, H., Salminen, K. and Andersson, P.H., 2008, Digital virtual holons - An approach to digital manufacturing systems, In: Mitsuishi, M., Ueda, K. & Kimura, F. (eds.) Manufacturing Systems and Technologies for the New Frontier, The 41st CIRP Conference on Manufacturing Systems, Tokyo, Japan, May 26-28: 103-106

[12] Wiendahl, H.P. and Heger, C.L., 2005, Justifying Changeability - A Methodical Approach to Achieving Cost Effectiveness, The International Journal for Manufacturing Science & Production, 6/1-2: 33-40

[13] Tsoukas, H., 1996, The Firm as a Distributed Knowledge System: A Constructionist Approach, Strategic Management Journal, 17: 11-25

[14] Alavi, M. and Leidner, DE., 2001, Knowledge Management and Knowledge Management Systems: Conceptual Foundations and Research issues, MIS Quarterly 25: 107-136

[15] Nonaka, I. and Takeuchi, H., 1995, The Knowledge-Creating Company: How Japanese Companies Create the Dynamics of Innovation. Oxford University Press, Oxford

[16] Kühn, W., 2006, Digital Factory - Integration of simulation enchanging the product and production process towards operative control and optimization, International Journal of Simulation, 7/7: 27-39

[17] Maropoulos, P.G., 2003, Digital enterprise technology-defining perspectives and research priorities, International Journal of Computer Integrated Manufacturing, 16/7-8: 467-478

[18] Souza, M.C.F., Sacco, M. and Porto, A.J.V., 2006, Virtual manufacturing as a way for the factory of the future, Journal of Intelligent Manufacturing, 17: 725-735

[19] Reiter, W.F., 2003, Collaborative engineering in the digital enterprise, International Journal of Computer Integrated Manufacturing, 16/7–8: pp 586-589

[20] Offodile, O.F. and Abdel-Malek, L.L., 2002, The virtual manufacturing paradigm: The impact of IT/IS outsourcing on manufacturing strategy, International Journal of Production Economics, 75: 147-159

[21] Bracht, U. and Masurat, T., 2005, The Digital Factory between vision and reality, Computers in Industry, 56: 325-333

[22] Dilts, R., 2005, Modeling, Robert Dilts NLP Home Page, Retrieved: 15th July 2008, http://www.nlpu.com/Articles/artic19.htm

[23] Law, A.M. and Kelton, W.D., 2000, Simulation modeling and analysis, 3rd ed. McGraw-Hill, New York

[24] Law, A.M. and McComas, M.G., 1999, Simulation of Manufacturing Systems, In: Farrington PA, Nembhard HB, Sturrock DT and Evans GW (eds), Proceedings of the 1999 Winter Simulation Conference, Squaw Peak, Phoenix, AZ, 56-59

[25] Sohlenius, G., 2005, Systemic Nature of the Industrial Innovation Process - Contribution to a Philosophy of Industrial Engineering, Doctoral dissertation No. 527, Tampere University of Technology, Finland