Next Generation
Manufacturing Systems

NGMS

White Paper

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CAM-I Next Generation Manufacturing Systems Program
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Introduction

CAM-I is an international not-for-profit collaborative research organization with offices in USA, Europe and Japan. Its research activities have been on the cutting edge of technology for the last 27 years and have literally changed the face of modern industry. CAM-I is industry-based, driven, owned and governed. Its sole purpose is to support member companies in their quest for excellence in today’s highly competitive global market place.

The CAM-I Next Generation Manufacturing Systems (NGMS) Program is an international consortium drawing together 22 companies and 11 research groups in the USA, Europe and Japan. The unique strength of the NGMS Program is its systems approach. Starting with the Next Generation Manufacturing Enterprise (NGME) vision, the NGMS Program has adopted a needs-based understanding of the future manufacturing systems.

The objective of the NGMS Program is to develop the best ideas on advanced manufacturing systems to serve the Next Generation Manufacturing Enterprise (NGME). The key issues of NGMS have to do as much with the ability to integrate manufacturing technologies and processes as with the technologies and processes themselves. The major strategy to achieve the Program objectives is to propose and conduct pre-competitive research and development projects as part of the international Intelligent Manufacturing Systems (IMS) initiative. CAM-I is the international Coordinating partner and Program Manager.

Key industrial and socio-economic issues

Economic and industrial communities’ worldwide will be subject to the increasing impact of competitive pressures resulting from the globalization of markets and supply chains to supply these markets. They will also be subject to great pressure to produce the final product locally to the market while still operating globally. For manufacturing enterprises in any given region to survive and prosper, they will need to make the most of economic and industrial opportunities. The NGMS-IMS project is providing a portfolio of methods and tools with which companies in a given region can equip them to compete successfully in the global market place.

In NGMS we believe that the future for manufacturing lies with new forms of manufacturing strategies based on global networks of self-organizing, autonomous units. These units may be part of one company (legal entity), located globally, or part of several companies, all co-operating to address the customers’ requirements. Whether it is one company or a network of several companies (a supply chain or virtual enterprise) demands on the manufacturing systems are very different from those in use today. The NGMS Program is developing...
the new manufacturing systems to support these new manufacturing strategies – next generation manufacturing systems.

These networks of companies, or supply chains need to rapidly adapt to changing requirements, new technologies, merging of existing technologies and increased globalization. Shorter response times will not allow for experimentation and iteration with the real thing; each new grouping of autonomous units must work at its optimum from the start where all decisions will be made on the basis of modeling and simulation, rather than build-and-test methods. The entire supply chain (or virtual enterprise) will be modeled and simulated prior to actual operation allowing alternatives to be tried and evaluated quickly.

To enable this to happen requires the development and testing of new forms of modeling systems, simulation systems, communication systems and information exchange systems.

**NGMS objectives and scope**

The NGMS Program is undertaking pre-competitive research and developments utilizing approaches based on virtual reality, biological or self-organizing manufacturing, scalable manufacturing concepts and open communication architectures to develop new manufacturing strategies – Next Generation Manufacturing Systems.

The IMS Steering Committee approved the NGMS-IMS Project in November 1995 and work started in January 1996. We are now approaching the end of this four-year period of work in December 1999. The goals of the NGMS-IMS project are to:

- Develop a unifying description of NGMS, an NGMS requirements definition that captures the results of the individual RTD activities and a framework for ensuring that the results are capable of being integrated into the cost effective next generation manufacturing systems.
- Develop a set of models and simulation approaches that are capable of being integrated to merge a bottom-up view of manufacturing flow (as will be found in NGMEs) with a top-down view of the globally distributed virtual enterprises.

NGMS addresses most manufacturing sectors. Participants come from automotive, aerospace, construction, electronics, manufacturing research, chemical plant construction, cable manufacture and shipbuilding.

The Partners of the CAM-I NGMS Program have brought together four central concepts of a Next Generation Enterprise:
• Agility (USA) (Agile Manufacturing Enterprise Forum 1991)
• Fractal Company (Germany) (Warnecke 1993)
• Autonomous & Distributed Manufacturing Systems (Japan) (Japanese IMS Domestics Program 1994)
• Biological Manufacturing Systems (Japan) (Japanese IMS Domestics Program 1994).

Rather than try to address the whole scope of the manufacturing enterprise, NGMS concentrates on the product-related functions:

• Integrated product and process design
• Production
• Logistics
• Post-sales service
• Information

The structure of the project is shown in Figure 1 below:

The project is divided into two Workpackages, each with several Tasks. Workpackage 1 is international with people form all three regions working together to produce the results. The planned activities in Workpackage 3 are more regionally focused with teams in each region working on a particular aspect of NGMS. Once the project had started it quickly became apparent to the members that considerable benefit could be realized by
researchers in two or more regions collaborating on a Task. Thus was born Task 3.6 the Collaboration Projects. To date five of these collaboration projects have got started.

**Workpackage 1**

This Workpackage provides the framework for the CAM-I NGMS-IMS Program and a guide for a company’s future manufacturing strategy. It provides a standard description of NGMS, defining key words and key concepts. It maintains the NGMS requirements as a timely and complete documentation of the vision and functions of NGMS.

It is also developing and maintaining an NGMS systems integration framework for evaluating the integration of the work products and to provide guidance on the integration of next generation manufacturing systems within companies.

**Workpackage 3**

Several approaches to modeling an NGMS have been suggested. In this Workpackage there are five major Tasks involving modeling and simulation for the NGMS from different perspectives. Four of these Tasks are being conducted primarily on a regional basis, with a fifth Task working cross-regionally.

**Task 3.1 – Modeling and Simulation for Autonomous and Distributed Manufacturing Systems**

This Task focuses on functional models of the production processes. It is derived from ongoing work in Japan on Autonomous and Distributed Manufacturing Systems (ADMS). It has three main components:

- ADMS Modeling and Simulation
- Autonomous Distributed Control
- Autonomous Decentralized Scheduling

**Task 3.2 – Virtual enterprise based global supply chains**

The objective of this Task is to propose and develop concepts and related methodologies to support the establishment, maintenance, change and operation of new forms of global supply networks based on virtual enterprise concepts. Work in Europe is particularly examining the virtual enterprise management concept and Internet techniques for rapid supply chain communication.

**Task 3.3 – Modeling for Biological Manufacturing Systems**

In this Japanese-led Task the basic models for Biological Manufacturing Systems (BMS) are being established. BMS seeks to realize the key NGMS characteristics using recent results from biology, molecular
biochemistry, and applied mathematics and computer science as related to artificial life. The Task is developing:

- A prototype Modelon system
- A proposal for product DNA
- A self-organizing simulator

Task 3.4 – Scalable Flexible Manufacturing
This U.S.-led Task is developing a framework for organizing resources consisting of hardware (machine tools, robots, CMMs etc.) and software (cell controllers, process planning software, operations planning software etc.) in computer automated environments. The developing framework is simple, modular, open, scalable, customizable and extendible and relatively platform independent.

Task 3.6 – Cross-regional Tasks
This is a collection of five cross-regional Tasks where researchers from Japan and Europe or Japan and USA collaborate on research activities; share ideas and produce combined international research results. This Task was not part of the original NGMS-IMS project proposal, but grew out of research and industrial contact at the Annual NGMS International Technical Conferences. The collaborations are:

- VR-SOS – A Europe/Japan project combining virtual reality with self-organizing simulation with a bi-directional connection such that the VR model drives the simulation model and visa-versa.
- E-SIM – A Europe/Japan project simulating enterprise activities. The activities include production, order receipt, management of parts and purchase of external parts. It has adopted the CIMOSA structure for modeling and utilizes VICTOR (based on SIMPLE++) for modeling and simulation.
- PAQ-K – A Europe/Japan concept for organizations aimed at producing higher productivity by rationalization and integration; better work life by decentralized information and decisions; increased quality systematization and improved equipment; and improved work as a way of acquiring knowledge.
- RD3S – A U.S./Japan development working on a new method for real-time decision support system for scheduling. The requirements are first, to generate a feasible solution in short time, second, to minimize any delay in product delivery times and third, to minimize as much as possible any process changes.
- GALAXI – A U.S./Japan study developing global algorithms for logistics analysis execution and integration. It is initially investigating the opportunities to improve the logistics of material movement within a U.S manufacturing plant. Upon a successful simulation the NGMS-IMS project partners will utilize the results from this research in other logistical environments.
Achievements

Considerable achievements have been made on a wide front during the four years of this phase of the NGMS-IMS project. They are described as follows:

NGMS Requirements and Systems Integration

The partners, working together, have developed a comprehensive set of characteristics and requirements for both next generation manufacturing enterprises (NGME) and next generation manufacturing systems (NGMS). The NGME characteristics can be summarized as follows:

- Re-configurability – the ability for fast, active adaptation to erratic and unpredictable environment changes.
- Capability of development – the ability to make evolutionary adaptations.
- Capability to manage turbulence – the ability to create and control turbulence in defined, demarcated markets
- Capability to realize changes – the ability and the readiness of all employees to change the internal structures
- Evolutionary capability – the ability to enable the enterprise by itself by analyzing the weaknesses and potencies of the past.
- Uniqueness – the permanent differentiation compared to the competitors
- Core competencies – competencies to produce unique core products, not only with knowledge but also with wide practical experience.

From this, a set of key requirements for NGMS have been determined:

1. Competitive in delivery time, quality and cost
2. Yielding satisfactory profit margins
3. Able to produce products and services in arbitrary lot sizes.
4. Be re-configurable, adaptable and flexible in response to customer needs.
5. Be an adaptive system
6. Be a learning system
7. Be able to collaborate across time, space and organizational boundaries.
8. Be interactive, sharing and simultaneous (concurrent) in operation and composed of self-sufficient, self-contained autonomous units.
9. Be human oriented
10. Be environmentally aware
11. Highly utilize new information and knowledge towards the enterprise goals.

CAM-I has maintained an NGMS Web Site as part of its overall CAM-I Web Site since the start of the project [http://cam-i.org](http://cam-i.org). This has contained both public and private sections. A new web site is being created (accessible through the NGMS private forum) in which all the deliverables can be accessed through a hypertext model.

During the life of the NGMS-IMS project several other initiatives, mainly in USA, have examined the imperatives for next generation manufacturing (NGM 1997, IMTR 1999). The NGMS requirements have been compared to and enriched by the findings of these studies. Thus the NGMS requirements encapsulate the best thinking in USA, Europe and Japan on next generation manufacturing systems requirements and characteristics.

The output of each Task in Workpackage 3 (modeling and simulation) has been analyzed in a standardized manner so that they can be compared and the different strengths better understood. The analysis used a 3-dimensional matrix against the NGME characteristics and the Fraunhofer IFF 2+4 enterprise perspective model\(^1\). The analysis then examined in a standardized manner the practicality, system requirements, restrictions/constraints and future approaches for each of the developments.

**Open Integration Platform**

The systems integration aspects of NGMS were originally envisaged only to encompass the integration of the developments within the NGMS-IMS project. However, it became apparent in the last year or so that we needed to give some guidance on how the various systems in NGMS’s could communicate within several virtual enterprises. This has led us into an investigation into open integration platforms (OIP). The work of several initiatives in this area, notably the European AIT (Advanced Information Technology) initiative and the U.S IMTR (IMTR 1999) were considered and a minimum set of OIP requirements have been specified:

- The OIP must fit with the NGME characteristics
- The OIP must allow for the integration of diverse applications, data sources and knowledge repositories
- The OIP must have a data philosophy of create once and use many.
- In the OIP, roles must be defined, with clear borders and ownership defined.
- The OIP must provide an agreed glossary
- The OIP must be able to evolve

\(^1\) Fraunhofer IFF 2+4 perspectives model: culture, strategy, socio-informal, finance, information, process/material flow.
• The OIP should strive to avoid proprietary systems
• The OIP should be as transparent and seamless to the users and the environment as possible.

This has only scratched the surface of a large and complex issue, but it has highlighted a number of key actions for the future.

**ADMS Modeling & Simulation**

Scene Transition Nets (an object oriented tool) and multi-aspect modeling have been used to develop some novel and unique approaches to the scheduling and control problem. They have developed an approach that allows for bottom-up model building using intelligent modules, integration through multi-aspect views, cooperation between modules and provides a powerful representative ability for both discrete and continuous systems. The results have been successfully demonstrated with examples of a chemical batch production process and an assembly line manufacturing system.

**Autonomous Distributed Control**

Agent net-based modeling has been applied to the control of autonomous distributed manufacturing systems. The agent net-oriented approach is a combination of Petri-nets and object-oriented approaches. The difference between this approach and more classical approaches is that the supervisory system does not allocate a particular resource to a job. Each resource makes a bid for the work and the best bid wins. This resource may then allocate the work to another one. The results of the simulation work have been tested on a model of a transportation system between docks and a model of a container yard.

However, the most convincing demonstration of the work is a vehicle transportation system. This utilizes a set of AGV, each being controlled by its own computer (see Figure 2).
In this demonstration the control is distributed to each AGV with the AGVs then co-operating with each other through the system administrator to complete their Tasks to accept jobs, re-rout jobs and avoid collisions between vehicles. The system administrator provides the high level request to the three autonomous AGVs and the AGVs co-operate (bid) on the request between themselves. Each AGV has a map of the floor layout and uses infrared sensors to update its location at each machine station. They do not follow any wires in the floor or an external guidance system. Although this approach is still only in the research stage one can quickly see the practicality of the approach and the benefits for industry over conventional approaches. These benefits include much simpler supervisory software, no need for guidance wires and thus ease of changing the layout, flexibility and extendibility of the system and more efficient use of AGVs.

**Autonomous Decentralized Scheduling**

The Task assumes that each unit in a factory is autonomous. It uses the approach of negotiation between the autonomous modules with a central “blackboard” containing order information and planning status information. The results have been tested in examples from a cable making facility and a steel rolling mill. The practicality of ADSS was confirmed by solving these examples using real plant data. ADSS has at least two advantages over conventional scheduling: namely minimal re-scheduling (short) time and more efficient scheduling results.
Internet Technique for the Supply Chain

This work is not yet complete, but achieving the goals set will deliver great benefits to all levels of the supply chain, particularly the smaller companies in the chains. The plan is that this Task will develop approaches whereby companies can use simple Web-based tools to communicate the product data and production data (order levels etc.) between each other without relying on proprietary systems or on each member of the supply chain having the same system. It will allow companies lower down the supply chain to have greater visibility of order levels higher up the chain and thus reduce the oscillations in the system. It is planned that in the next few months a prototype will be demonstrated showing the sharing of order in the supply chain using a Web Browser (e.g. Internet Explorer or NetScape Navigator).

Self-Organizing Simulation

The methodology Biological Manufacturing Systems (BMS) work on modeling and simulation has been concentrating of late on an example of lineless manufacturing. Instead of the normal production line, they have been simulating a system using AGVs and robots, where the robots are attracted by attraction and repulsion fields (see Figure 3). The whole system uses artificial life algorithms. The results indicate that the overall performance of a lineless operation is significantly improved over a linewise operation. The total facility cost is greatly reduced, based on BMS simulations. Higher robot availability is indicated with a good reduction in actual process times.

Figure 3
**Scalable Flexible Manufacturing**

Two industrial test cases have been initiated to test the Scalable Flexible Manufacturing (SFM) architecture. The first involves building a simulator of a component placement machine utilized for the production of a printed circuit board (PCB). The company expects that the research activities will result in reduced PCB design time as well as factory floor set-up and de-bug time when manufacturing a new and/or improved PCB. The second will seek to develop, demonstrate and validate a methodology and engineering process for SFM software that will assist in the reduction of time and effort spent in planning, specification, design, validation and deployment of manufacturing facilities. Test bed simulations indicate that architecture based on computer architecture principles can show significant gains in cell scalability and flexibility.

**Real-time Decision Support System for Scheduling**

The requirements for this Task were summarized into three major areas. First, to generate a feasible solution in short time, second, to minimize any delay in product delivery times and third, to minimize as much as possible any process changes. A hierarchical rule-based scheduling method that generates Meta-rules is the basis for the research efforts. Early results of the simulations complete on actual factory process data indicate that the tools developed could provide for improved factory operability at reduced manufacturing costs.

**PAQ-K Production Cell**

The objective of the research is to obtain high total performance of a production cell by means of cell combination and cell improvement through simulation and then to apply it to a real system. Early results indicate that integration between production cells and enterprises are not just about the flow of materials, the integration of people is critical. Studies have shown that not all technology-led changes succeed, mainly because technological changes are rarely just technological changes.

The joint Japanese/Swedish study has indicated a number of potential critical success factors for production cells:

- High competence among the members of the project team
- Education in the implementation stage
- Sufficient resources
- Appropriate staffing of the project team
- All participants are motivated
- Ability to build knowledge
- Involvement of company management
Integration of both management and shop floor employees

Company goals, visions and strategies communicated and accepted.

Sufficient knowledge to be able to evaluate vendor proposals

Global Algorithms for logistics, analysis, execution and integration

This Task is only in the early stages of research; therefore, only limited results are available. However, it is important to point out that the fundamental research efforts have been completed and preliminary results will yield the development of the mathematical model and the development of the simulation model by the end of 1999. Preliminary studies indicate the difficulty of balancing the utilization of logistical resources (trucks) with a smooth production schedule and visa-versa.

Virtual reality – self-organizing simulation

The Japanese and German groups working on Virtual Reality- Self-Organizing Simulation (VR-SOS) have successfully linked the VR systems in Germany with the SOS in Japan. The first links were uniquely coded links, but with the third example the link has now been made with a more universal tool. The effect is that this novel form of simulation (using attraction and repulsion algorithms) can drive the virtual reality model in real time, so that any changes made in the simulation show up in the virtual reality model. This is a bi-directional link so equally changes made in the virtual reality model (such as shop floor layout changes) will affect the simulation.

The results of this work offers industry a powerful set of tools to model and simulates production in a way that exposes poor layout and poor scheduling. It enables companies to develop their layout and production planning simultaneously and understand the interrelationship between them. Thus a new production facility can be designed, modeled, simulated and run virtually before any physical assets have been committed. The production facility should then operate as planned from initial start-up.

Need for international co-operative research

Globalization is greatly expanding the availability of new markets. This globalization is also spurring intense competition in all manufacturing sectors. All manufacturing enterprises are finding that manufacturing is ceasing to be a local or regional issue, companies must operate of a global stage or face extinction. Companies, both large and small, now have to follow their customers and produce locally to their ever-changing markets.
A recent report in Germany (Fraunhofer ISI 1998) indicated that 74% of German business people believe that the technological development and the global redistribution of workplaces increase permanently the average rate of unemployment on most developed countries. Thus companies have to set up in partnership with other companies around the world. They are increasingly being involved in virtual enterprises with global partners. Industry does not need a European or US or Japanese view of manufacturing systems, it needs a global view. Companies need to know what their potential partners and customers are thinking and expecting. Manufacturing systems will have to communicate around the world, not just down the street.

The NGMS-IMS project has shown, even in its early days, that the vision for manufacturing is remarkable similar in all regions. We have found that the greatest benefit to our work and the most excitement amongst industry and research participants has been the cross-regional projects. These grew out of a sharing of research ideas amongst the regions and have involved people from companies in one region visiting and working with people from companies in another region, often for several weeks at a time. The result has been some extraordinary developments that could not have been achieved by the research groups just working within their region. The international collaboration provided the spark and the vision to enable the researchers to lift their sights and see what might be possible.

International collaboration has been essential to the success of NGMS. Most European participants have stated that the benefit for them of the NGMS-IMS project is the ability to work with companies in U.S.A. and Japan.

**Benefits of the NGMS-IMS project**

The achievements of the Tasks within the NGMS-IMS project have been described above. These achievements and others will bring considerable benefits to companies. It is difficult to quantify many of the benefits as they are primarily aimed at helping companies change their manufacturing systems to be effective in a world of globally distributed manufacturing units. The overall benefit of adopting next generation systems will be to ensure their survival and future prosperity, nothing less. However, during the process of change the NGMS-IMS project will provide companies with the following more specific benefits:

- A framework and blueprint for the integration of future manufacturing systems into the new forms of manufacturing enterprises.
- Competitive advantage from a more rapid adoption of advanced systems, processes and technologies.
- More rapid and “right first time” establishment of networks of autonomous units through the application of new types of simulation methodologies and tools.
- More rapid and “right first time” establishment of manufacturing processes through the application of new types of simulation methodologies and tools.
- Greatly improved response times to changing customer needs through the adoption of new forms of modeling and simulation systems.
- Working on future manufacturing issues together with leading technologists and companies in Japan, USA and Europe who are addressing similar problems.
- A valuable shared learning experience on the latest technological developments in manufacturing systems and their applications that minimizes a company’s investment exposure in research and development without “reinventing the wheel”.

The future – Phase II

The NGMS-IMS project has reached the end of its first planned four-year cycle. It is now planning to extend the work into a second phase starting in January 2000 and finishing in December 2003. It is anticipated that this will be approved by the IMS International Steering Committee as an extension to the current IMS project.

As the NGMS-IMS project research and development activities were completed within the Phase I project it was realized that the results that were obtained actually defined the scope of the “Digital Factory”. Within a Digital Factory, production simulations and the simultaneous design of both product and production processes can be employed to reveal potential errors and/or conflicts at an early product and facility design stage. The facility simulations can also dramatically shorten the expensive period of production start-up, which often lasts for several months. Further, utilizing the concept of the Digital Factory, the factories of an NGME can truly be designed and simulated within a virtual computer network. Within this Digital Factory simulation the factory performance can be simulated before cutting any metal or turning any earth for the factory, which in turn could result in timesaving of up to 30 percent in the factory start-up and operation.

In NGMS-IMS Phase II the Digital Factory concepts will be addressed in all aspects of the research and development activities. As in Phase I the project partners in Phase II are coming from Europe, Japan and the United States of America. Phase II will consist of four Workpackages, each with several Tasks:

1. Description, characteristics, requirements and information integration

   To provide the framework of the NGMS-IMS project
   - Description of Next Generation Manufacturing Systems
   - Characteristics and requirements of NGMS
   - NGMS systems integration and modeling tools
4. **Knowledge based information systems**
   To provide the computing and communications that enable production procedures and technology to be communicated intelligently using the concept of the Digital Factory as well as multi-media (including Virtual Reality) that can be flexibly adapted to changes in production and operation.
   - Production cells for knowledge intensive products, good work life and high quality (KPAQ)
   - Integration of horizontal product information with vertical business information
   - Integrated manufacturing and resource planning (IM-RP)

5. **Information systems for effective global value networks**
   To develop new and improved information technology methodologies and prototypes to facilitate integration of design and production activities and to improve logistics across the extended enterprise, including the eventual disposal of products once their useful life has been completed.
   - Developing the reverse supply chain information system
   - Global algorithms for logistics, analysis, execution and integration
   - Total optimization of manufacturing, transportation and logistics system
   - Knowledge discovery in product development and manufacturing

6. **Reconfigurable manufacturing systems**
   To develop a reconfigurable, flexible computer automated Digital Factory manufacturing systems that can scale by modular construction to high and low volumes of production.
   - Scalable flexible manufacturing
   - Development and verification of control executives for manufacturing cells
   - Networked interactive manufacturing and optimization
Acknowledgements

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