Final Technical Report for Project Entitled

Presidential Young Investigator Award: Design and Development of a Manufacturing Enterprise Architecture

Submitted to

National Science Foundation
4201 Wilson Blvd.
Arlington, VA 22230

PYI Award Number: DDM-8957861

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Georgia Tech Project #: E-27-651

June 28, 1996

SJ-TR-NSFPYI-9606

OMB Number 345-0058

NATIONAL SCIENCE FOUNDATION
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PI/PD Name and Address

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Atlanta GA 30332

NATIONAL SCIENCE FOUNDATION FINAL PROJECT REPORT

PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org.	Donald Gross - DMI
2. Program Name	OPERATIONS RESEARCH & PRODUCTION SYSTEMS
3. Award Dates (MM/YY)	From: 10/89 To: 03/96
4. Institution and Address	GA Tech Res Corp - GIT Administration Building Atlanta GA 30332
5. Award Number	8957861
6. Project Title	Presidential Young Investigator Award: Design and Development of a Manufacturing Enterprise Architecture

This Packet Contains
NSF Form 98A
And 1 Return Envelope

NSF Grant Conditions (Article 17, GC-1, and Article 9, FDP-11) require submission of a Final Project Report (NSF Form 98A) to the NSF program officer no later than 90 days alter the expiration of the award. Final Project Reports for expired awards must be received before new awards can be made (NSF Grants Policy Manual Section 677).

Below, or on a separate page attached to this form, provide a summary of the completed projects and technical information. Be sure to include your name and award number on each separate page. See below for more instructions.

PART II - SUMMARY OF COMPLETED PROJECT (for public use)

The summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the project title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent to the project being described, the following items:

- The primary objectives and scope of the project
- The techniques or approaches used only to the degree necessary for comprehension
- The findings and implications stated as concisely and informatively as possible

PLEASE SEE ATTACHED. THANKS.

PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

PLEASE SEE ATTACHED. THANKS.

I certify to the best of my knowledge (1) the statements herein (excluding scientific hypotheses and scientific opinion) are true and complete, and (2) the text and graphics in this report as well as any accompanying publications or other documents, unless otherwise indicated, are the original work of the signatories or of individuals working under their supervision. I understand that willfully making a false statement or concealing a material fact in this report or any other communication submitted to NSF is a criminal offense (U.S. Code, Title 18, Section 1001).

	June 28, 1996
Principal Investigator/Project Director Signature	Date

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<u>Part II Summary of Completed Project</u>

An important prerequisite for the successful implementation of Computer-Integrated Manufacturing (CIM) in an enterprise is a detailed knowledge and understanding of the functions and information associated with the enterprise. Such a definition of the manufacturing enterprise is known as the *architecture* of manufacturing. A standard architecture would reduce the overall system complexity and enable users to build systems in increments. The Manufacturing Enterprise Architecture (MEA), developed in this research, is the framework that captures, represents and integrates the three major facets of an enterprise, viz., *function*, *information* and *dynamics*.

The overall objective of this research effort has been to design and develop MEA which will serve as a blueprint for the creation of a Computer-Integrated Enterprise (CIE). The research encompassed several complementary activities which led to the following significant accomplishments: creation of domain-specific models for yarn, fabric, apparel and carpet manufacturing enterprises; demonstration of the domain-independence of the manufacturing architecture through application of the architecture to healthcare delivery; design and development of a new methodology, viz., integrated framework for enterprise modeling methodology (IFEM); implementation of the IFEM methodology using object-oriented programming techniques resulting in the Enterprise Modeling Framework (EMF); design and development of specialty fabrics for ballet costumes using innovative CAD/CAM techniques for The Atlanta Ballet and the Centennial Cultural Olympiad; and transfer of technology and knowledge gained during the research to companies through graduates and collaborative case studies.

Part III Technical Information

1. INTRODUCTION

To be successful, competitive, and achieve excellence in today's global economy, a manufacturing enterprise must reengineer its operations and deploy the most advanced concepts and methods including Computer-Integrated Manufacturing (CIM). The scope of CIM transcends the traditional boundaries of the factory floor and encompasses the whole enterprise, giving rise to a Computer-Integrated Enterprise (CIE). A CIE can be defined as an enterprise that utilizes computers for the engineering, planning, manufacturing, marketing and business functions of the enterprise, and for the integration of all these functions into a cohesive enterprise system through a common information/knowledge base.

2. NEED FOR AN ENTERPRISE ARCHITECTURE

An important prerequisite for the successful realization of a CIE is a detailed knowledge and understanding of the functions and information associated with the enterprise. Such a definition of the manufacturing enterprise is known as the *architecture* of manufacturing. A standard architecture would reduce the overall system complexity and enable users to build systems in increments. The Manufacturing Enterprise Architecture (MEA), developed in this research, is the framework that captures, represents and integrates the three major facets of an enterprise, viz., *function*, *information* and *dynamics*.

3. RESEARCH OBJECTIVE AND SCOPE

The overall objective of this research effort has been to design and develop MEA which will serve as a blueprint for the creation of a CIE. The research has encompassed the following complementary activities aimed at realizing the overall objective:

- o Design and development of domain-specific architectures;
- o Illustration of the domain-independence of the manufacturing architecture through its application to *healthcare* systems;
- o Development of enterprise modeling methodologies using major software engineering techniques and tools including object-oriented programming and databases;
- o Investigation of the role of concurrent engineering in the textile/apparel complex;
- o Investigation of methodologies for justification of investments in information technologies and systems;

- Systematization of domain-specific knowledge and its harnessing for instructional purposes using multimedia technology; and

- Design and development of specialty yarns and fabrics using computer-aided design and manufacturing techniques for ballet costumes in collaboration with The Atlanta Ballet.

4. SUMMARIES OF RESEARCH ACCOMPLISHMENTS

The major highlights of the various research activities carried out as part of the PYI Award are presented here; the references cited for the various activities provide details of the accomplishments.

4.1 Domain-Specific Architectures

The first step toward developing a *generic* manufacturing enterprise architecture (MEA) was to develop domain-*specific* architectures; these domain-specific models could then serve as the basis for the necessary generalization. Among the many sectors of the American industry facing intense foreign competition accompanied by the erosion of the manufacturing base and loss of employment opportunities is the textile/apparel sector. For this reason, the textile/apparel environment was chosen as the initial test bed for the development of the domain-specific manufacturing architectures.

A set of criteria was devised for evaluating and selecting modeling methodologies [5] for developing the architecture. Based on these criteria, several methodologies were evaluated; the IDEF methodology -- developed under the US Air Force's ICAM Program -- was selected. The details on the Yarn and Fabric Manufacturing Architectures can be found in [16]; the details of the Function model of the Carpet Manufacturing Architecture can be found in [3]. The Apparel Manufacturing Architecture (AMA) is discussed in [10, 13, 14]. The research on AMA received funding from the US Defense Logistics Agency under DLA-900-87-D-0018.

4.2 Domain-Independent Architecture

As the domain-specific architectures were being developed, the possibility of creating a domain- or industry-*independent* architecture was explored. The models were generic enough at higher levels (e.g., product development, production planning, and distribution) to represent other sectors of manufacturing besides textiles and apparel. At the lower levels, however, information specific to the domain needs to be modeled. The details of these concepts vis-a-vis the product continuum that ranges from commodity-type items to specialized items can be found in [4]. The role of knowledge and experience in operating an enterprise are also discussed in [4]. Several key issues germane to research in the area of integrated architectures for manufacturing were also identified.

4.3 Healthcare Delivery Systems Architecture

To further explore the concept of a domain-independent architecture and the application of the manufacturing architecture to non-manufacturing domains, research was carried out in collaboration with pediatricians in a group practice. The healthcare delivery system was viewed as a manufacturing enterprise and the research resulted in the healthcare delivery system architecture [2, 12, 27]. This effort conclusively demonstrated the concept of the domain-independent modeling methodology and architecture.

4.4 Enterprise Modeling Methodologies

During the course of this research, several major shortcomings in the IDEF methodology were identified and a new methodology termed IFEM (integrated framework for enterprise modeling) was proposed [14, 15]. The proposed schema can serve as the foundation for the development of manufacturing systems modeling software. Such an enterprise modeling methodology is essential in the context of implementing advanced concepts of Quick Response and Just-in-Time manufacturing in an enterprise.

MEA consists of three models, viz., *entity* model, *activity* model and *knowledge & beliefs* model to encompass the function, information and dynamics facets of an enterprise. A detailed discussion of the three models can be found in [28]. MEA overcomes the shortcomings of IDEF and other modeling methodologies and has the following salient features [29, 31, 34]:

- o An Entity model based on a Semantic (Object-oriented) Data Model.
- o An Activity model with both *IS-A* and *PART-OF* hierarchies of manufacturing functions.
- o Seamless integration of the Entity and Activity models: the interface between activities is defined as Views on Entities; the editing and browsing tools for MEA have been designed for working concurrently on both the models; automatic consistency maintenance between the two models.

The *conceptual* schema proposed in [28] for MEA was implemented in software using CLOS, an object oriented programming (OOP) language [29, 30]. LispView was used to build the user interface conforming to OpenLook standards. Graphical tools for browsing through the Activity and Entity models were developed; the dynamics script has been integrated into the Activity model. The resulting Enterprise Modeling Framework (EMF) represents a significant contribution to the domain of enterprise modeling methodologies [17, 32, 33, 34, 35].

4.5 Concurrent Engineering in the Textile/Apparel Complex

The textile/apparel industry is probably one of the most dynamic manufacturing industries; this is because textiles and clothing are seasonal and the consumer is increasingly fashion, value and quality conscious. The discerning consumer is seeking unique styles and the ability to choose from a wide variety of fabrics (woven, knitted) made from a range of yarns (staple, filament), which in turn are made from an array of fibers (natural, man-made). Moreover, when the consumer doesn't find the specific item in the retail store, the consumer seeks alternatives and the potential sale may not materialize. Therefore, the ability to respond quickly to market trends is yet another important operating requirement for the textile-apparel complex [9]. This means the product and the associated manufacturing processes should be engineered to facilitate rapid production. The role of *concurrent engineering* in realizing these goals was explored [8].

4.6 Justification of Investments in Information Systems and Technologies

Information is the lifeblood of an enterprise, especially when a manufacturing enterprise needs to rapidly reconfigure itself -- change designs, materials, styles, production techniques, etc. -- in response to consumer demands and market trends [11]. The ability to successfully harness this valuable resource in a timely and well-coordinated fashion calls for investments in information systems and technologies. Investments in such technologies, however, cannot always be justified using traditional techniques such as net present value, return on investment and payback period. This is because such investments may provide competitive, strategic and tactical advantages that may not be as tangible as operational benefits (e.g., savings in personnel costs and improved operator productivity). The primary objective of this research effort was to explore the various issues related to the development of a methodology for justifying investments in information systems and technology.

The life-cycle view of an information system/technology (IS/IT) project was used to explore issues related to the development of a methodology for justifying investments in information systems and technology [1]. Preliminary findings indicated that there were no specific or well-defined methodologies used by organizations to justify investments in IS/IT and suggested the need for additional research in this area.

4.7 Systematization of Domain-specific Knowledge

The proliferation of powerful and inexpensive hardware/software systems has paved the way for innovative applications of information technology in the classroom. The first step towards building such multimedia-based intelligent tutoring systems is the *systematization* of domain knowledge and the development of a taxonomy for knowledge representation. Therefore, research was carried out to develop the knowledge representation schema for the domain of textile engineering; the schema was subsequently used to implement a tutoring system, TEESS, under MS-Windows using VisualBasic [25]. The system is expected to serve as a tool for imparting textile engineering knowledge to freshman students and new hires in the textile industry. Additional work is currently in progress to take advantage of the recent advancements in Web Browser technology and the World Wide Web.

4.8 Computer-Aided Design and Manufacturing of Specialty Textiles

The success of an enterprise depends, among other things, on its ability to effectively utilize advanced modeling methods and technologies in its operations, especially in the design and manufacturing facets. Therefore, to demonstrate the concepts of an integrated approach to the design and manufacturing of textiles, research was carried out on two major fronts: The first was aimed at modeling the structure-property relationships of yarns produced under various manufacturing conditions. The second was the design and development of a specialty fabric to meet the functional and aesthetic requirements of ballet costumes.

As part of the structure-property relationships research, the use of artificial neural networks for the prediction of yarn tensile properties was explored [26]; this effort turned out to be the first of its kind in textile research literature. The details of the studies and models can be found in [20, 21, 22, 23, 24].

The research on producing the specialty fabric was carried out in collaboration with The Atlanta Ballet [19]. Working with the ballet dancers, the characteristics (*functional* and *aesthetic*) required of the fabric were developed; these were then used to *engineer* the required yarns and fabrics using CAD/CAM systems. The fabric was used in the costume worn by the ballerinas during performances of the Atlanta Ballet and led one of them to remark "*this is the best costume I have ever worn in my career; I felt like I had nothing on me during the program ....*". Considering the fact that the human *skin* is the *ultimate garment* for the human body, this remark testifies to the research accomplishments and also demonstrates the true fusion of art and technology. The fabric has been continuously improved over the past three years and the most recent version will be featured as part of The Atlanta Ballet's performances during the upcoming Cultural Olympiad in Atlanta [18].

5. EDUCATION AND TECHNOLOGY TRANSFER

Several graduate students (4 PhD and 9 MS), 3 post-doctoral fellows, 2 research associates and 3 additional faculty members participated in the various research efforts during the course of the Award, and thus were able to pursue their research interests. In addition, the program afforded the PI the opportunity to write a textbook and Instructor's Manual for an introductory computing course for engineers [6, 7]. However, the Award funds were *not* used to support this activity.

The developed technologies have been transferred to the industry through two main channels: (i) collaborative efforts on case studies with industry; and (ii) the subsequent employment of graduates by major companies such as UPS (United Parcel Service), Intel, US Sprint and FedEx. The research results have also been transferred to the students in classroom settings in Senior and Graduate level courses at Georgia Tech, and at a *NATO Advanced Study Institute* (ASI) on Mechatronics held in Turkey.

In summary, during the course of the PYI Award, considerable progress was made towards realizing the complementary goals of:

- o advancing knowledge and the state-of-the-art in manufacturing systems;
- o transferring technology to the industry; and
- o educating the future generation of scientists and engineers.

Acknowledgements

Thanks are due the National Science Foundation for the PYI Award (DDM-8957861) which enabled the researchers to carry out various exciting projects summarized in this report. Thanks are also due Hewlett-Packard Company for providing the matching funds for the PYI Award through an equipment and software grant. An additional equipment grant from Sun Microsystems in support of the research is also thankfully acknowledged. The industry partners who served as test beds also deserve thanks and appreciation. Finally, the contributions of the PI's current and former graduate students, and colleagues towards accomplishing the research objectives are reflected in this report and various publications; these individuals also deserve sincere thanks and appreciation for their participation.

* * *

List of Publications

[1] Etheridge, S., Gilley, D., Narasimhan, L., Narasimhan, S., and Jayaraman, S., "Justification of Information Technology Projects", SJ-WP-IT-9209, Working Paper, Georgia Institute of Technology, Atlanta, Georgia 30332-0295.

[2] Govindaraj, T., and Jayaraman, S., "Healthcare Delivery Systems: An Enterprise Modeling & Simulation Perspective", AMIA 1994 Spring Congress, San Francisco, CA, May 4-7, 1994.

[3] Hamilton, G., "Design and Development of a Carpet Manufacturing Architecture: The Function Model", MS Thesis, Georgia Institute of Technology, Atlanta, Georgia, June 1996.

[4] Jayaraman, S., "On a Manufacturing Enterprise Architecture", IJCAI '89 (International Joint Conference on Artificial Intelligence) Workshop on Manufacturing, Detroit, MI, August 21-25, 1989.

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[6] Jayaraman, S., Computer-Aided Problem Solving for Scientists and Engineers, New York, NY: McGraw-Hill, Inc., February 1991, 432 pages.

[7] Jayaraman, S., Instructor's Manual to Accompany Computer-Aided Problem Solving for Scientists and Engineers, New York, NY: McGraw-Hill, Inc., September 1991, 210 pages.

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[11] Jayaraman, S., "Computer-Aided Design and Manufacturing: A Textile-Apparel Perspective", in Advancements and Applications of Mechatronics Design in Textile Engineering, (Acar, M., Ed.), Kluwer Academic Publishers, The Netherlands, pp. 239-269, 1995.

[12] Jayaraman, S., and Ramesh, M.C., "Healthcare Delivery System Architecture: The As Is Function Model of a Pediatric Group Practice", Technical Report SJ-TR-NSFPYI-9501, Georgia Institute of Technology, Atlanta, Georgia, January 1995.

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[15] Malhotra, R., and Jayaraman, S., "An Integrated Framework for Enterprise Modeling", Journal of Manufacturing Systems, vol. 11, no. 6, pp. 426-441, 1992.

[16] Narasimhan, B., "Design and Development of an Architecture for Information Management in a Manufacturing Enterprise", MS Thesis, Georgia Institute of Technology, Atlanta, Georgia, March 1994.

[17] Narasimhan, B., Navathe, S., and Jayaraman, S., "On Mapping ER and Relational Models Into OO Schemas", Lecture Notes in Computer Science #823 Entity-Relationship Approach - ER'93, (eds: Elmasri, R.A., Kouramajian, V., and Thalheim, B.,), Springer-Verlag, Berlin, Germany, pp. 402-413, 1994.

[18] Novina, T., "Textiles in the Olympics", America's Textiles International, pp. 62-66, June 1996.

[19] Park, S., "Studies on Effect of Fiber Properties and Fabric Structure on Fabric Hand", MS Thesis, Georgia Institute of Technology, Atlanta, Georgia, March 1995.

[20] Rajamanickam, R., "Studies on Fiber-Process-Structure Property Relationships in Air-jet Spun Yarns", PhD Dissertation, Georgia Institute of Technology, Atlanta, Georgia, December 1995.

[21] Rajamanickam, R., and Jayaraman, S., "A Computer Simulation Approach for Engineering Air-Jet Spun Yarns", to appear in Textile Research Journal.

[22] Rajamanickam, R., and Jayaraman, S., "An Analysis of the Modeling Methodologies for Predicting the Strength of Air-Jet Spun Yarns" to appear in Textile Research Journal.

[23] Rajamanickam, R., and Jayaraman, S., "Studies on Fiber-Process-Structure-Property Relationships in Air-Jet Spinning, Part I: Effect of Process and Material Parameters on the Structure of Microdenier Polyester/Cotton Blended Yarns", submitted to Journal of the Textile Institute, April 1996.

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[25] Ramanan, P.S., "A Multimedia-based Learning Environment for Textile Engineering Education", MS Thesis, Georgia Institute of Technology, Atlanta, Georgia, June 1995.

[26] Ramesh, M.C., Rajamanickam, R., and Jayaraman, S., "The Prediction of Yarn Tensile Properties by Using Artificial Neural Networks", Journal of the Textile Institute, vol. 86, No. 3, pp. 459-469, 1995.

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[28] Srinivasan, K., and Jayaraman, S., "MEA: An Object-oriented Framework for Enterprise Modeling", Proceedings of the AAAI '91 Workshop on OOP in AI, Anaheim, CA, July, 1991.

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[33] Srinivasan, K., and Jayaraman, S., "EMF: A Modeling Environment for Hierarchical Specification and Simulation of Enterprise Dynamics", Technical Report SJ-TR-NSFPYI-9310, Georgia Institute of Technology, Atlanta, Georgia, October 1993.

[34] Srinivasan, K., "Design and Development of an Enterprise Modeling Framework", PhD Dissertation, Georgia Institute of Technology, School of Textile & Fiber Engineering, Atlanta, Georgia, December 1993.

[35] Srinivasan, K., and Jayaraman, S., "Comparison of Object-Oriented Programming Languages: The Enterprise Modeling Framework Perspective", Journal of Object-Oriented Programming, pp. 27-32, June, 1994.

Note: The regular reports in the Proceedings of the NSF DDM Grantees Annual Conference are not listed here.

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E-27-651

#6

PART IV -- FINAL PROJECT REPORT -- SUMMARY DATA ON PROJECT PERSONNEL

(To be submitted to cognizant Program Officer upon completion of project)

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in resonse to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the nformation.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

	Senior Staff		Post-Doctorals		Graduate Students		Under-Graduates		Other Participants[1]	
	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male	Fem.
A. Total, U.S. Citizens	1					3				
B. Total, Permanent Residents	3		2							
U.S. Citizens or Permanent Residents[2]:										
American Indian or Alaskan Native										
Asian..........................										
Black, Not of Hispanic Origin.........										
Hispanic........................										
Pacific Islander..................										
White, Not of Hispanic Origin										
C. Total, Other Non-U.S. Citizens										
Specify Country 1. INDIA			1		7	1			1	
2. KOREA						2				1
3.										
D. Total, All participants (A + B + C)	4		3		7	6			1	1
Disabled[3]										

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1] Category includes, for example, college and precollege teachers, conference and workshop participants.

[2] Use the category that best describes the ethnic/racial status fo all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3] A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

AMERICAN INDIAN OR ALASKAN NATIVE: A person having origins in any of the original peoples of North America and who maintains cultural identification through tribal affiliation or community recognition.

ASIAN: A person having origins in any of the original peoples of East Asia, Southeast Asia or the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

BLACK, NOT OF HISPANIC ORIGIN: A person having origins in any of the black racial groups of Africa.

HISPANIC: A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

PACIFIC ISLANDER: A person having origins in any of the original peoples of Hawaii; the U.S. Pacific territories of Guam, American Samoa, and the Northern Marinas; the U.S. Trust Territory of Palau; the islands of Micronesia and Melanesia; or the Philippines.

WHITE, NOT OF HISPANIC ORIGIN: A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.