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Design of effective e-Work: review of models, tools, and emerging challenges

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Keywords active protocols, active middleware, autonomous agents, collaborative robotics, collaborative work, conflict resolution, distributed operations, enterprise integration, enterprise models, parallelism, teamwork evaluation, viability

Abstract. The foundations and scope of e-Work are described, and investigations of fundamental design principles for e-Work effectiveness reviewed. The premise is that without effective e-Work, the potential of emerging and promising electronic work activities, such as virtual manufacturing, telerobotic medicine, automated construction, intelligent transportation, and e-business, cannot be fully materialized. A typical and recent example of the inability to fulfill the potential of e-Work is the frustration of workers over supply chains/networks with complex ERP and other information systems, originally designed to simplify and improve their performance. Challenges and emerging e-Work solutions are described, and recent discoveries are clustered in four areas, e-Work; Integration, Coordination and Collaboration; Distributed Decision Support; and Active Middleware, with annotated references. PRISM Center developments of e-Work design principles, models and tools are described, including: Cooperation Requirement Planning; the principle of parallelism; the principle of conflict resolution; new measures of viability and scalability; and the Teamwork Integration Evaluator (TIE), which applies the analogy of distributed computing.

1. Introduction: definitions and scope of e-Work

As power fields, such as magnetic fields and gravitation, influence bodies to organize and stabilize, so does the sphere of computing and information technologies. It envelops us and influences us to organize work systems in a different way, and purposefully, to stabilize work while effectively producing the desired outcomes.

e-Work was defined by the PRISM Center (Nof 1999, 2000a, 2000b) as any collaborative, computer-supported and communication-enabled productive activities in highly distributed organizations of humans and/or robots or autonomous systems (figure 1). In essence, e-Work is comprised of e-activities, namely, activities based on and executed through information technologies. In figure 1, those e-activities include v-(virtual)Design, e-Business, e-Commerce, Intelligent Robotics, e-Manufacturing, v-(virtual)Factories, e-Logistics, i-(intelligent) Transportation, and v-(virtual)Enterprises. All these e-activities rely on computer support and communication technologies, and all of them require collaboration in their inherent interactions between machine, humans, and computers. Other examples of e-activities that comprise e-Work are telemedicine, e-Learning, e-Training, navigation and security monitoring by geographic information systems (GIS), and more. e-Work includes applications such as telerobotics (e.g. Brady and Tarn 2000, Hamel 2000) and remote medical and health services (e.g. Meng *et al.* 2000, Rovette 2000). Some have defined e-Work as Telework (Chiozza and Stanford-Smith 2001, Burgess 2003) and indeed, Telework can be part of e-Work according to the general definition above.

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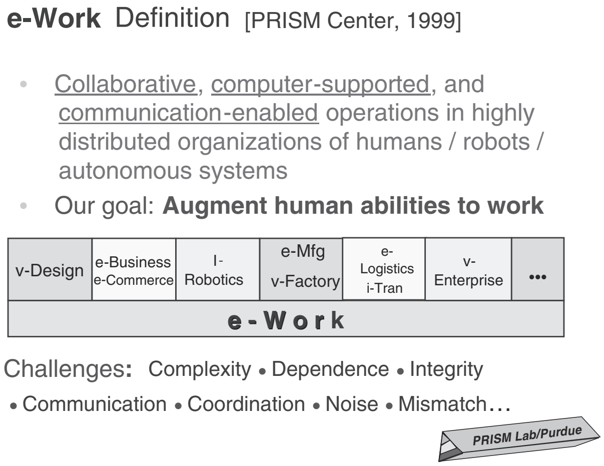

Figure 1. The original definition of e-Work, its goal and challenges (Nof 1999, 2000a, 2000b) (v-Design; Virtual Design; I-Robotics: Intelligent Robotics; v-Factory: Virtual factory; i-Tran: Intelligent Tranportation; v-Enterprise: Virtual Enterprise).

Several conferences on e-Work as Telework have taken place since 2000 (Cheshire Henbury 2003). Increasingly, however, it is recognized that human work has been and still is being fundamentally transformed, as it has been throughout history, by the combination of social organization and technology advancements (table 1).

The principles of the work system have been transformed, and the focus of concern in the design of work systems has changed. While advancement in technology over time has increased the ability to work and produce, the challenges and complexities have also increased, and seem to be increasing at an exponential rate. As shown in table 1, the present challenge with e-Work systems is to reduce, and possibly optimize both the information overload and the task overload.

The objective of this article is to describe the foundations and scope of e-Work, and review investigations of fundamental design principles for e-Work effectiveness. The premise is that without effective e-Work, the potential of emerging and promising electronic work activities, such as virtual manufacturing, telerobotic medicine, automated construction, intelligent transportation, and e-business, cannot fully materialize. A typical and recent example of the inability to fulfil the potential of e-Work is the frustration of workers over supply chains/networks with complex ERP and other information systems, originally designed to simplify and improve their performance. Even if the human–computer interface for such systems is highly effective, the information overload and expectations from the human operators can be overwhelming. Effective production of the best outcomes may not occur.

The view of e-Work as the foundation of e-activities (figure 1) implies that there are work abilities that can be significantly better enabled by information technologies, for example:

- Better connectivity and ability for farther global reach.
- Enhanced communication and coordination.
- Acceleration of knowledge sharing and distribution.
- Better interactivity, flexibility, customization-ability.

Table 1. Fundamental changes in the evolution of work systems.

Period	Technology advancement	Human work augmented by	Fundamental work system principle	Engineering & management concerns	Work system goal[1]
Before the Industrial Revolution	Hand-tools	Tooling	Manual and animal power	Work methods	Enable work functions
Before Computers	Engines; Machines	Power; Motions; Moves	Human-machine systems	Work flow	Reduce muscle load
Computer Age	Computers; Communication; Robots	Control; Data processing; Automation	Computer-aided and computer-integrated systems	Human–computer interaction; Human–robot interaction	Reduce information overload
Information Age	Telecom; Internet; Mobility	Cognitive skills; Collaboration	e-Work	e-Work design; Collaboration; Parallelism	Reduce information and task[2] overload

[1]Goals beyond productivity, quality, safety, etc.
[2]Both cognitive and non-cognitive tasks

- Higher velocity of work tasks and exchanges.
- Reduced communication costs.
- Lower cost of work transactions.
- Lower agency cost by replacing humans with software agents (eliminating the middle people).

Hence, e-activities enhance the opportunities for better, more productive work, and at the same time, they widen the competition. But despite the advantages entailed with e-Work, there are common challenges:

- Greater work complexity.
- More limitations caused by increasing interdependence.
- Issues of integrity and trust.
- Greater need for coordination, cooperation, and synchronization.
- Communication challenges and failures, complicating systems' requirements.
- Problems of mismatch, e.g. inconsistent versions, cultural differences, etc., also complicating systems' requirements.
- New users training requirements and associated costs.
- The infancy stage of research, leading to applicability limitations, and to hesitation in acceptance by potential users.

Failing to overcome these common challenges may explain why often, e-activities do not fulfil the expectation promised by technology.

How is e-Work different from e-Business and e-Commerce? The same way work is different from business and commerce. They are highly related, but not the same. Figure 2 depicts some of the scope differences.

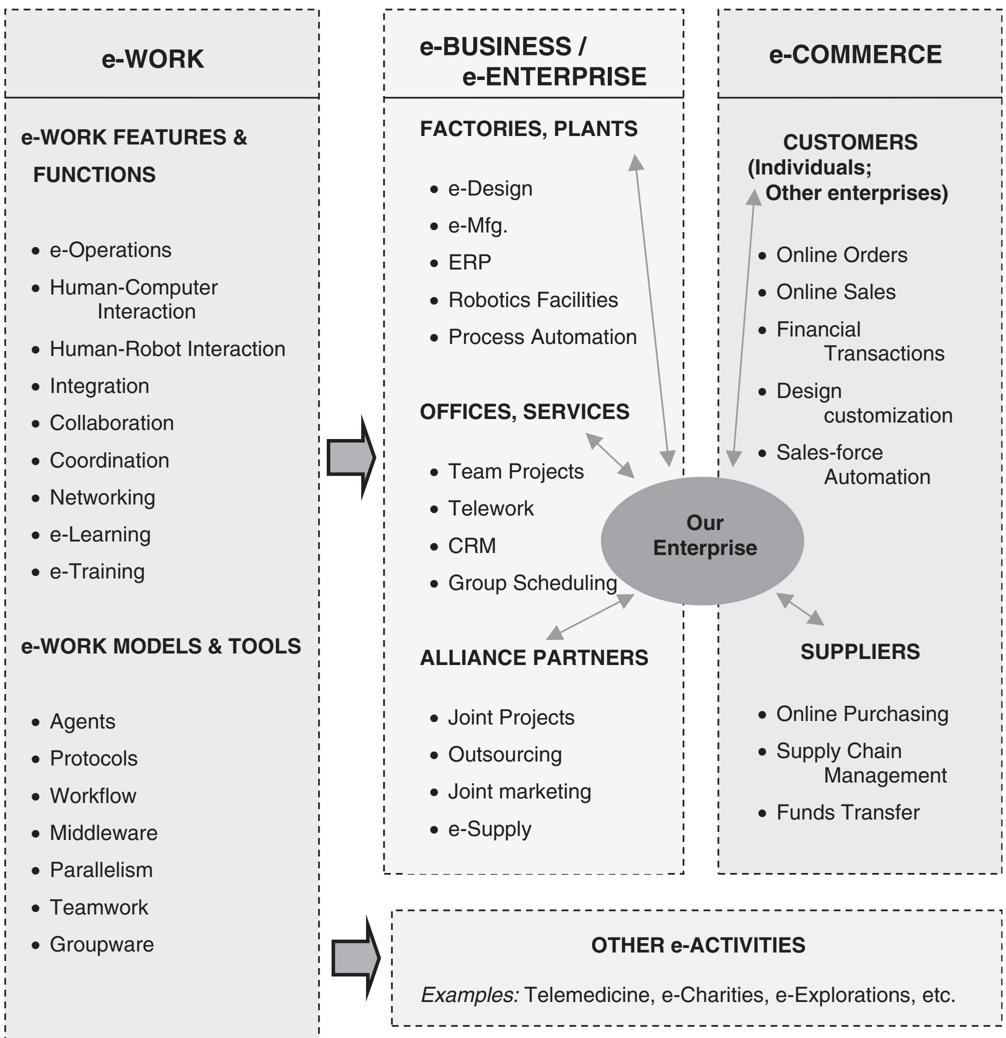

Figure 2. e-Work is fundamental to e-Business, e-Commerce, and other e-activities (just as work is fundamental to business, commerce, and other activities).

Table 2. Examples of e-work cases with telecommunication.

e-Work enabled by communication	Non-internet based	Internet based	Combination
Distributed computing and information exchanges			
1. e-Mail	✓	✓	✓
2. Teleconference	✓	✓	✓
3. EDI (data interchange)	✓	✓	✓
4. EFT (fund transfer)	✓	✓	✓
5. Product design	✓	✓	✓
6. Distance learning	✓	✓	✓
7. On-line information search	✓	✓	✓
8. Automated teller machine (ATM)	✓	✓	✓
9. Supermarket self-checkout	✓	–	–
10. Virtual reality for training	✓	*	–
11. Virtual reality for design	✓	*	–
12. GRID based teamwork	*	–	–
Collaborative robotics/human-robot teams			
13. Telerobotic nuclear reactor repair	✓	–	–
14. Telerobotic mining	✓	–	–
15. Networked test and inspection	✓	✓	✓
16. Robotic space exploration	✓	*	–
17. Robotic construction	✓	–	–
18. Tele-assembly in clean room	✓	–	–
19. Diagnostics by sensor web	✓	–	–
20. Telesurgery	✓	–	–
21. Medical imaging and diagnostics	✓	*	–
22. Robotic laser drilling	✓	–	–
23. Robotics in home healthcare	✓	*	–
24. Virtual reality with haptic devices	*	–	–

*Emerging

One way to define the distinction between these three related areas is:

e-Commerce: Commercial e-exchange among customers and providers (suppliers). This exchange is mostly between separate, external entities.

e-Business: Same e-exchanges as in e-Commerce, except the emphasis is on internal e-operations and e-services within the scope of a given enterprise.

e-Work: e-operations and e-support to enable the above two, as well as many non-commercial and non-business work activities, from creative artistic projects, education and learning, to medical help, charity activities, police work, scientific exploration, and many more productive work endeavors.

The main reason to distinguish e-Work is the realization that there are certain common principles in the design of effective e-Work, without which e-activities cannot succeed. It can be said that 'To do good e-Business, somebody has to do good e-Work' (Nof 2001).

e-Work depends on communication, including telecommunication. The Internet has influenced many of the tele-operation areas, yet there are e-Work activities that clearly do not depend on the Internet. Table 2 shows examples of Internet-based e-Work and non-Internet based e-Work, as well as some that are enabled by both.

2. Major challenges and emerging e-Work solutions

During the industrial ages *Before Computers* (Table 1), 'Human–Machine Systems' challenged engineers and managers to solve interference issues, namely, how to coordinate and synchronize human workers, machine operations, and material flow in and between factories. Planning and control systems were mostly manual.

With the *Computer Age*, new concerns emerged, increasingly, for better **Interaction** and for **Integration** ('from islands of automation to total systems, from local optimization to global optimization'). These concerns reflected the challenges of new work abilities to interface more complex systems, involving more information transfers, many more transactions, and the dawn of computer and robot servitude: Beginning the delegation of control and cognitive tasks from humans to computers, machines, and robots. The area of Human–Computer Interaction (HCI) joined the areas of Industrial and Systems

Engineering, and Management Sciences, to address the myriad of interaction and integration challenges.

One of the main new concerns has been **Information Overload.** It means that humans, each with a single brain, have to interact and contend with computer-based systems and machines that may have certain superior skills not only in physical tasks, but also in information handling and computing. (Usually, a computer-based system has been developed by many humans and contains accumulation of vast knowledge). The objective has been to reduce the information overload (only for the humans) by better design of interfaces and of computer systems, and by more training for the human users/participants.

Another natural solution has been the increasing reliance on **Teamwork**, not only in physical tasks, but increasingly in design and engineering, planning, control, supply, and management tasks. Concurrent design, concurrent engineering, total information systems, and total quality management are examples of the urge to team and collaborate to solve an increasingly complex world of production and service. Further teaming has been evident in the trend of outsourcing. **Outsourcing** certain tasks of production and services is, practically, teaming with external enterprises. The models of **supply chains and supply networks** reflect further teaming among enterprises. Obviously, the enabling technologies of computer communication increased the human ability to share and exchange information:

- among team members;
- among distributed machines and robots, including tele-operations and sensors; and
- among producers, suppliers, distributors and customers.

But at the same time, computer communication has increased the complexity and challenges for human workers and for the designers of work-systems.

The advent of the *Information Age* has enabled new levels of work augmentation, including telecommunication, computer Internetworking, and mobile computing. With these new powerful dimensions of work abilities, the area of e-Work has emerged. Telecommunication and the Internet significantly impact the cost and time of e-activities, in certain ways potentially increasing them, in other ways potentially reducing them. For example:

- The cost and the time to execute information-based transactions, per transaction, (e.g. design change, production order, purchase order, invoicing, training, inspection, etc.) are reduced. On the other hand, the volume of transactions to correct errors, overcome conflicts, and allow for needed customization changes and responses may increase the overall cost of transactions.
- The cost of agency (all the 'middle-people') and the needed layers of agency are reduced. On the other hand, the lack of agency services requires more efforts of coordination and synchronization by the remaining layers of work.
- Outsourcing becomes attractive by delegating tasks to those who specialize in the outsourced work and can reduce costs and delivery time. At the same time, the cost and time of performance may actually increase because of the added needs for coordination and communication among the distributed parties.

The significant reductions in information transfer-cost and response-time in the *Information Age* explain the proliferation of distributed networks of producers, suppliers, consumers and customers. At the same time, there is further growth, to the point of explosion, in **Information Overload and Task Overload** across larger markets and wider distributed networks of operations. The development and emergence of solutions to these challenges are described in the next section.

3. The four circles of the 'e-' in e-Work

An overview of the recent related research about the 'e-' in e-Work is shown in figure 3. The four circles reflect four clusters of knowledge. Significant amount of such knowledge relevant to e-Work has appeared in the literature; the representative sample of references in figure 3 include work by members of the IFAC (International Federation for Automatic Control) Committees on Manufacturing and Logistics Systems (for which the author is the current Chair), by the PRISM Lab at Purdue, and leading work by others, with an annotated reference list at the end of the article. A brief description and some future challenges of each of the 15 subareas of e-Work appear in the following paragraphs. It is intended that this presentation will stimulate and inspire fruitful future investigations, revolutionizing the way that beneficial e-Work can be designed.

A. e-Work

A1. *Theory and models*

e-Work is a collaborative, computer-supported, and communication enabled operation in highly distributed organizations of humans/ robots/ autonomous systems. A goal of e-Work is to augment human abilities to work. Information technologies will yield benefits

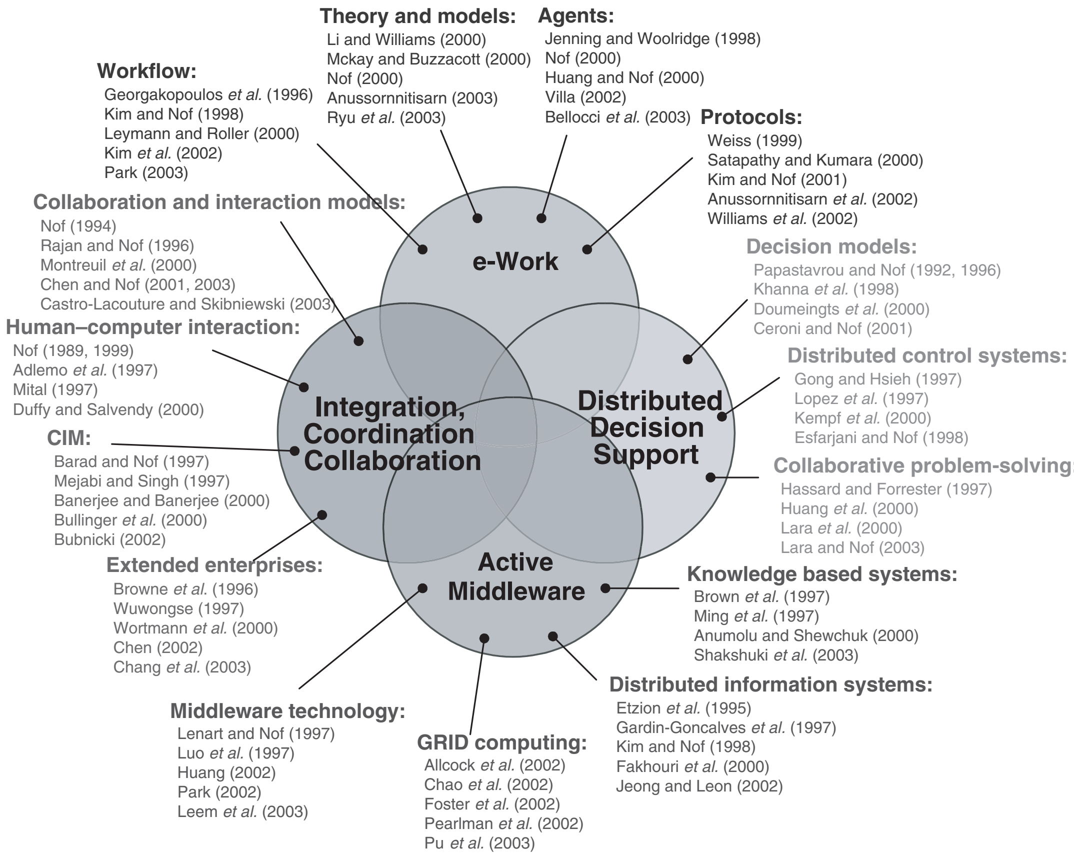

Figure 3. e-Work: foundations, tools, and emerging discoveries.

through e-Work if they are constructed based on proven theories and design principles.

Currently, e-Work enabling technologies in computing and communication are rapidly being developed. Planning how to harness these technologies to enhance the users' ability to work and enjoy the quality of results will depend on layers of integrated services and support (HCI clearly being one of them). e-Work theory and models help to define and match the right e-Work system and integrate it to improve or optimize operations and decisions.

Future research on e-Work will focus further on the realization of the theory, and models for specific applications.

A2. *Agents*

The role of agents (with work protocols and active middleware, which are described below) is to enable efficient information exchanges at the work application level, and perform tasks, under protocol control, to ensure smooth, efficient interactions, collaboration, and communication, which augment the natural human work abilities. An **agent** has been defined as a computing hardware and/or software system, that is able to (non-autonomously, or autonomously) interact with other agents and its environment, act, and respond reflexively to external impacts in accordance with its given goals.

Intelligent agents (knowbots, softbots, and robots) are software and hardware entities that perform a set of tasks on behalf of a user with some degree of autonomy. They are a useful computational paradigm for creating systems that are flexible, adapt to changes of the environment, and are able to integrate heterogeneous components and tasks. They find applications in a variety of domains including: Internet-based information systems, adaptive (customizable) software systems, autonomous mobile and immobile robots, data mining and knowledge discovery, smart systems, decision support systems, and intelligent design and manufacturing systems. Recent research on intelligent agents and multiagent systems builds on developments in several areas of computer science, including: artificial intelligence (especially agent architectures, machine learning, planning, distributed problem solving), information retrieval, database and knowledge-based systems, and distributed computing and problem solving.

In future research, rapid development of agent system and human–agent integration to assist interaction processes, such as business workflow, automated negotiation and conflict resolution, will lead the agent-based systems into the mainstream information technology solutions.

A3. *Protocols*

Protocols at the work application level (as opposed to computer communication protocols), such as Task Administration Protocols (TAP) (Nof 1995) are defined as the logical rules for workflow control. Protocols enable effective collaboration by communication and resource allocation among production tasks. In active protocols, 'active' implies that the protocol can, under coordination logic, trigger and initiate necessary timely interaction tasks and decision-support functions to further improve performance.

In distributed systems, e.g. multiagent systems, coordination protocols are used to guide and support the automated interaction of each agent or an autonomous entity in order to achieve the common goal of a system. The efficient coordination process will lead to effective collaboration, especially in large distributed systems, e.g. Internet, GRID computing, or network of enterprises. Recent research includes the development of coordination protocols and protocol evaluation for a particular system, such as auction based protocols, resource allocation protocols, and negotiation protocols. For example, time-out protocols have been developed for better task allocation in client–server work-cells (e.g. Esfarjani 1994, Peralta *et al.*, 2003), and adaptive time-out protocols have been developed for rationalized resource-sharing in assembly-and-test facilities applying the TestLAN approach (e.g. Williams 1994, Williams *et al.* 1998, 1999, 2002, 2003). Auction-based protocols have been developed and analysed by parallel simulators (figure 4) for distributed task and resource allocation in multiagent systems (e.g. Anussornnitisarn 2003).

In future research, more complex coordination processes, such as multiparticipant negotiation processes, group decision mediation, and conflict management processes will be developed. In addition, the dynamic characteristics of the protocol which acts or reacts to the stochastic nature of distributed environments will be of interest.

A4. *Workflow*

Workflow is an information technology that helps in guiding and processing business and engineering activities that can be defined to adapt to the changing needs of a dynamic environment, especially when the processes are no longer intra-enterprise operations. Current research in this area focuses on enabling technologies to provide scalability, availability, and performance reliability. Traditional enabling technologies have been DBMS (Data Base Management Systems), message queuing systems, and transaction processing systems. This set of technologies is usually referred to as middleware that integrates the interenterprise operations, regardless of the computing platforms. More advanced workflow models will apply dynamic optimization and machine learning techniques to manage events in complex networks (Kim and Nof 2000, 2001, Kim *et al.* 2002).

Future research in this area will focus on complex interactions for more effective and responsive integration, leading to better collaboration effectiveness. In addition, workflow control will not only guide the process, but also involve detecting and solving errors before or when they occur.

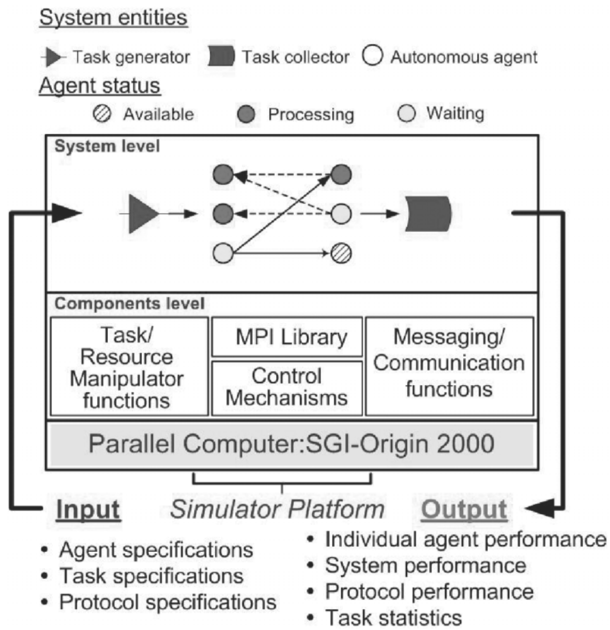

Figure 4. TIE/protocol simulator for protocol design evaluation (Anussornnitisarn and Nof 2003).

B. Integration, coordination and collaboration

B1. *Collaboration and interaction model*

The model of collaboration and integration helps system developers identify the link between information resources and information processing entities. The right model will improve the performance of collaborative work in terms of flexibility, reliability, and quality of information exchange. Current research focuses on developing computer-supported collaborative work tools, and the model of information required by distributed team members and exchange of information among them.

Future research will develop decision-making tools by distributed and autonomous team members who have different priorities and objectives, and formulation of resolutions (agreements) among distributed collaborators.

B2. *Human–computer interaction (HCI)*

Human–computer interaction is an interdisciplinary subject, which involves areas such as computer science, engineering, education, psychology and informatics. The purpose of HCI is to develop computer systems that support people in their roles as learners, explorers, and workers. A current research focus is on developing advanced user interfaces that help users to efficiently interact with and through computer-based application systems. Another area is the study of usability, which measures the level of human ability to benefit from objects and systems.

Future challenges include human–computer interaction not only to explore the installed body of information, but also to discover new knowledge via intensive information exchange, similar to the brainstorming process among humans.

B3. *Computer integrated manufacturing (CIM)*

Computer Integrated Manufacturing research has focused on developing the field of automated manufacturing and material handling, and the application of computing to design, machine, and manufacture products, including quality management and process control (see example in figure 5). Recent research on CIM, has involved the development and management of the entire product lifecycle by blending several technologies, including design and manufacturing; process planning; manufacturability analysis; production

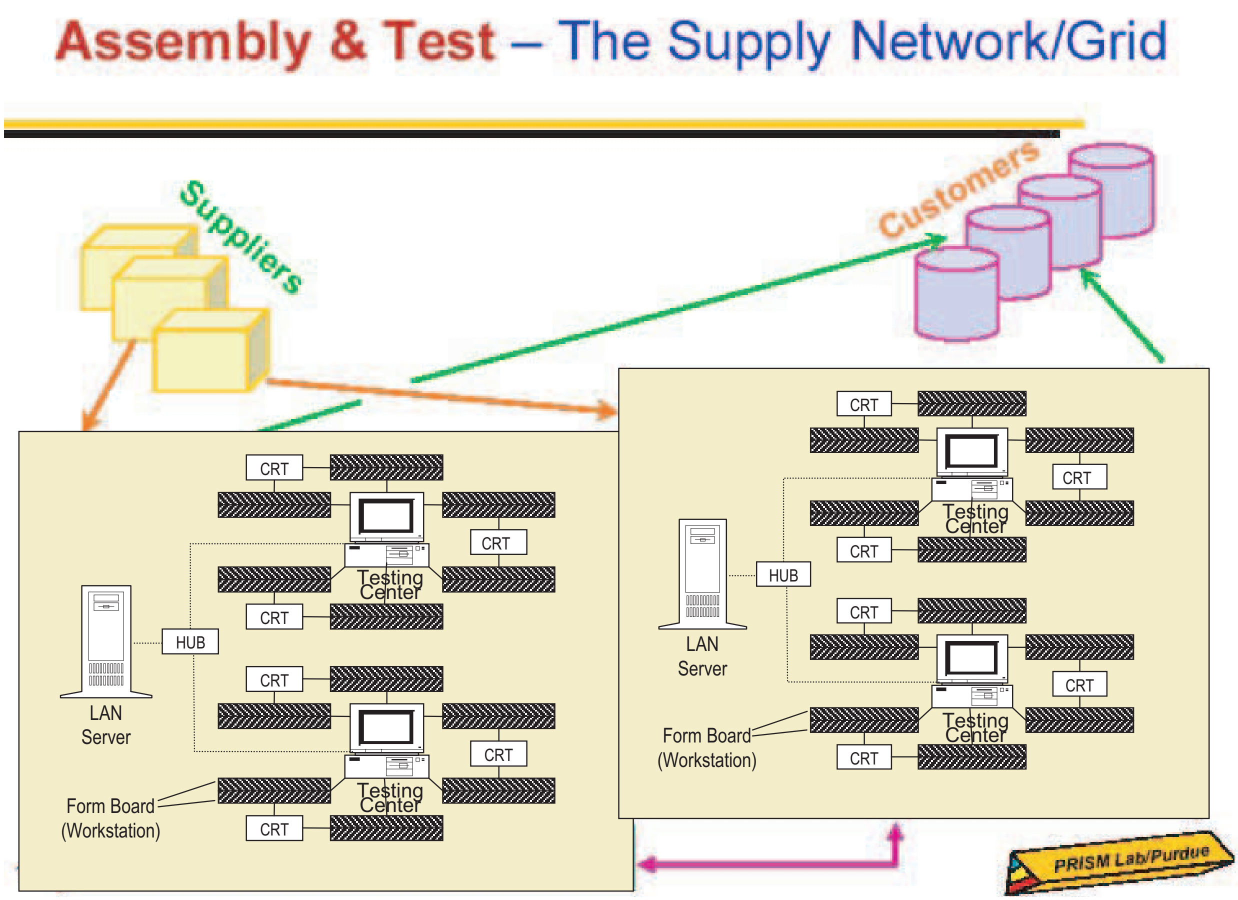

Figure 5. From e-Work inside assembly facilities with TestLAN, to e-Work across supply networks and emerging supply grids (Nof 2003).

planning and scheduling; manufacturing system design; and system integration.

There are two emerging research areas for CIM: (1) Distributed support tools that govern the information flow among distributed manufacturing units that must act under time, budget, manufacturing and environmental constraints, (2) The infusion of MEMS and nano sensors to collect and to handle information for more intelligent real-time control and decision making in active process control systems.

B4. *Extended enterprise*

Extended enterprise research is another outcome of advances in information technology. Powerful communication of information enables the integration of enterprise business processes beyond a single enterprise, including functions and software applications from end-to-end, not only internal but also for entire supply chains/networks (see Figure 5). Currently, the focus of research is on models and methodology to deliver real-time information to enable collaboration with customers, employees and business partners in a connected economy, with faster response and better decisions.

In the future, research will have to address also the area of real-time decision making, execution, and conflict management among collaborators across the supply network.

C. Distributed decision support (DSS)

C1. *Decision models*

The value of decisions that are based on the decision-theoretic approach depends on the quality of available information and the underlying models. Computer assistance in modelling can significantly reduce the model construction time, while increasing the quality of the model, and can contribute to a wider applicability of decision theory in on-line decision support systems. Current research focuses on the development of general-purpose knowledge representation languages with the normative status and well-understood computational properties of decision-modelling formalisms and algorithms.

Future research will focus further on interaction-based decision models with distributed knowledge sources, and human interactions, which would allow the decision structures to be adaptive and more responsive.

C2. *Distributed control system (DCS)*

Distributed control systems allow the parties associated with a system to negotiate for their tasks and their benefits. Autonomy is a key characteristic to classify the type of DCS. Current research focuses on systems with low level of autonomy among partners, such as job shop scheduling, where global objective functions are usually given.

Future research will focus on systems with higher level of autonomy, such as networks for supply chains, where each enterprise continues to hold its own goal and agenda, but can compromise to achieve faster satisfactory common goals. Similarly, in distributed robotic teams, cooperation requirement planning will be integrated with collaborative execution of tasks (figure 6).

C3. *Collaborative problem-solving*

The collaborative problem-solving approach applies information exchange to influence other parties about collaborators' local decisions, to act coherently and to achieve a better result for the entire organization (system). Current research focuses on the development of methodologies and quality of solutions to mostly predefined problems. For example, several initiatives have been developed to address the needs of predefined problems of training personnel in the armed forces. The Field Artillery School has examined the type of

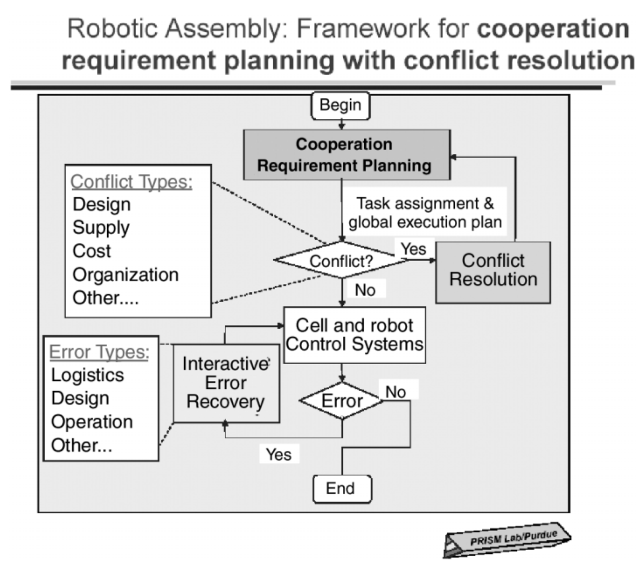

Figure 6. An e-Work framework for robotic assembly as an example of integrated support of cooperation planning; error diagnostics, prevention and recovery; and conflict diagnostics, prevention, and resolution (Chen and Nof 2003).

collaboration necessary between military decision makers and staff units by using information handling decision-support systems in a battlefield setting. The US Army Armor School has investigated how students can collaborate from remote sites to role-play with several staff positions in a virtual tactics operations center.

Future research will have to open up the possibility of collaboration among loosely-coupled entities, where less mutual benefits are acceptable, or even required among the collaborators.

D. Active middleware

D1. *Technology*

Middleware constitutes a set of services that aim at facilitating the development of distributed applications in heterogeneous environments. In a way, middleware represents the human functions of 'middle people' (see section 2). The primary objective of middleware technology is to foster application portability and distributed application component interoperability. Middleware operates at a layer below the application and above the operating system and network layer. Common enabling technologies include CORBA, DCOM, Java RMI, MQSeries, and MSMQ. Recent research focus in middleware technologies is on the development of middleware architecture to provide active services to clients of the system. Similar to active protocols, the active middleware adds intelligence to the behaviour of e-Work activities and interactions.

In the future, the active middleware service will target more the very large scale computing platform which has characteristics of highly heterogeneous, autonomous, and distributed components, beyond the typical enterprise network.

D2. *GRID computing*

Grid computing (often shown as the term GRID) allows access to geographically distributed computing resources. It enables sharing, selection, and aggregation of a wide variety of widely dispersed computing nodes, such as supercomputers, computing clusters, storage systems, data sources, instruments, and people as a single, unified resource for solving large scale and data intensive computing applications. Current research focuses on the computational economy, on the development of Grid computing architecture and its components, such as a scheduler (see figure 7).

The future of this area will be the development of service applications which will explore the potential of the Grid computing paradigm in both scientific and business applications.

D3. *Distributed information system (DIS)*

The merging of computers and communications with significant advances in networking infrastructure has made accessible millions of information sources with wide varieties of information. The goal of current research is to develop techniques to design distributed information systems, coordinate the distributed computation, provide security methods, and maintain high reliability and integrity of the overall information network. Corporate memory systems, e-Learning, and e-Training are examples of DIS applications. The current focus is on the development of system architecture, standards, and methodologies to maintain high quality of service for the large scale of distributed information networks, e.g. search robot, XML data management, and semantic web.

In future research, distributed information systems will be more interactive with users in order to acquire and extract knowledge as it develops in its distributed information environment, and to serve the complex needs of users. A major challenge in DIS is the analysis and control of ripple effects when one or several nodes in the distributed network fail. For instance, security methods in DIS must detect and provide the means to handle and prevent any damages that could be caused by intrusion at any point of the system, to assure total system performance.

D4. *Knowledge-based system (KBS)*

Knowledge-based systems focus on the use of knowledge-based techniques to support human decision making, planning, learning, and action. Such systems are capable of cooperating with human users. The quality of support given and the manner of its presentation are important issues. Current research focuses on the construction and extraction of knowledge from and for a variety of information resources.

Future research will focus more on integrating KBS with other technologies to assist a human user or a group of users to make a better decision, especially in large scale distributed information systems, and for complex unstructured problems involving high levels of uncertainty.

The four-circle context of e-Work, discussed in this section, can be summarized along 15 e-dimensions, as shown in table 3. These e-dimensions seem appropriate for the design of an effective, modern work system. Four

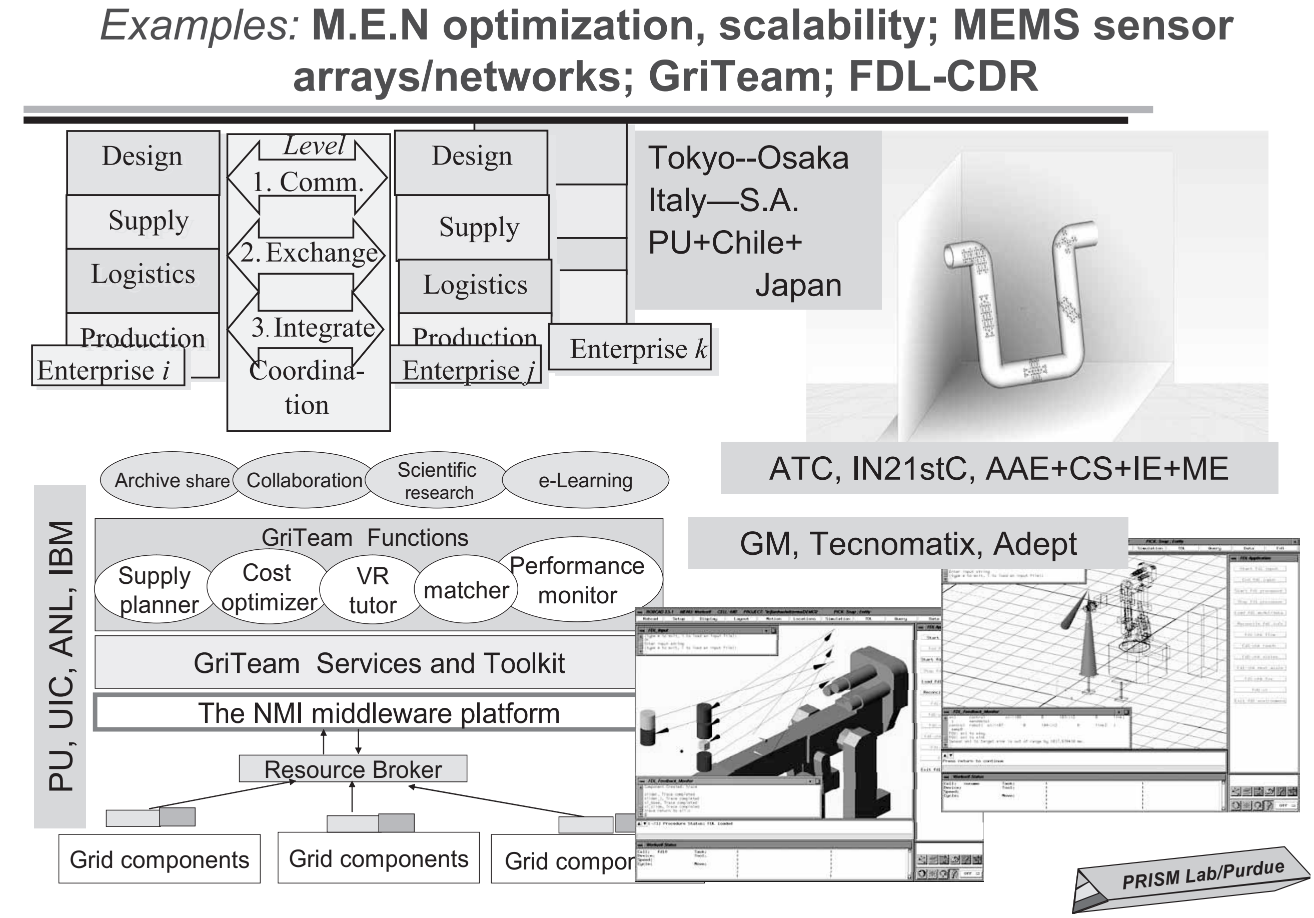

Figure 7. Four recent examples of e-Work research and the participating organizations and sponsors. The scope illustrated includes (clockwise from top-left) multi-enterprise network design; micro sensor arrays along arteries; co-design with conflict resolution support; and the emerging Grid-based teamwork (GriTeam). (Participants' acronyms: S.A. – companies in South America; PU – Purdue University; UIC – University of Illinois, Chicago; ANL – Argonne National Lab; IBM – IBM Corp.; ATC – ATC, Inc.; IN21stC – Indiana 21st Century Fund for Science and Technology; AAE – School of Aeronautical and Astronautical Engineering; CS – Department of Computer Science; IE – School of Industrial Engineering; ME – Mechanical Engineering, all at Purdue University; GM – General Motors Corp.; Tecnomatix – Tecnomatix Technologies, Inc.; Adept – Adept Technologies, Inc.)

challenges for distributed e-Work design principles can be summarized as follows:

(1) Modelling and optimization of coordinated interactions among autonomous entities for smooth transitions towards a common goal;
(2) managing and controlling the growth arbitrariness for optimal viability and scalability;
(3) information assurance: security, integrity, and significance of the information which 'fuels' e-Work, and
(4) handling errors and conflicts to enable the above three without major disruptions.

The next section describes some of the most recent research and discoveries attempting to respond to these challenges.

4. PRISM Center developments of e-Work design principles

During research projects for over a decade, it has become clear that e-Work represents a new, exciting and challenging model of work systems. With an ever increasing scope of distributed and decentralized work activities, increasing distribution and magnitude of world-wide markets, e-Work brings opportunities for better work methods, outcome and yield by augmenting human physical, cognitive, temporal, and locational abilities to work. However, it has also been evident that e-Work is associated with new complex needs and new design challenges. Table 4 summarizes a sample of projects attempting to understand the new requirements and challenges, and develop useful theories and solutions for them.

Table 3. The 15 e-dimensions of e-Work research thrusts (Nof 2003a).

Area	Emerging thrust	Role	Future challenges
A. e-Work			
A1. Theory and models	Collaborative, computer-supported and communication-enabled operation in highly distributed organizations of humans/ robots/ autonomous systems.	Augment human abilities to work.	Development and realization of the theory and models for specific applications.
A2. Agents	Software and hardware entities that perform a set of tasks on behalf of a user with some degree of autonomy.	Useful for creating systems that are flexible, adaptive to changes, and able to integrate heterogeneous components and tasks.	Development of agent system and human–agent integration to assists interaction processes
A3. Coordination protocols	Guide and support the automated interaction of each agent or an autonomous entity in order to achieve the common goal of a system.	Efficient coordination processes will lead to effective collaboration, especially in large distributed systems.	Coordination of multiparticipant negotiations, group decision mediation, conflict management.
A4. Workflow	Information technology to help guiding and processing business and engineering activities in a dynamic environment, especially when processes extend beyond the organization's boundaries.	Enabling process scalability, availability and performance reliability.	Better collaboration effectiveness, including detecting and solving errors when they occur.
B. Integration, coordination, and collaboration			
B1. Theory and models	Computer-supported collaborative work tools and models of information exchange among distributed team members.	Helping system developers identify the link between information resources and information processing entities, to improve the performance of collaborative activities.	Decision making by distributed and autonomous team members, and formulation of resolutions among distributed collaborators.
B2. Human–Computer Interaction (HCI)	Advanced interfaces to help users efficiently and effectively apply computer systems.	Develop systems that support people in their role as learners, explorers, and workers.	Beyond exploring installed bodies of information, discover new knowledge via intensive information exchange, similar to human brainstorming.
B3. Computer Integrated Manufacturing (CIM)	Automated manufacturing and materials handling, and computer application to design, machining, and manufacturing of products and services, including quality management and process control.	Integration and management of the entire product life-cycle.	1) Distributed support tools governing flow under time, budget, manufacturing, and environmental constraints; 2) Embedding MEMS and nano sensors for intelligent real-time control and interactive decision making.
B4. Extended enterprises	Models and methods for better delivery of real-time services in collaboration with customers, employees and business partners in a connected economy.	Integration of business processes beyond the single enterprise, including end-to-end functions, internal operations, and entire supply chains.	Real-time decision making, execution, and conflict management among collaborators over the supply network.

C. Distributed decision support			
C1. Decision models	General-purpose knowledge representation languages with normative status and well-understood computational properties of decision-modelling formalisms and algorithms.	Computer assistance in modelling can significantly reduce the model construction time while increasing model quality, and contribute to a wider applicability of decision theory in on-line decision support systems.	Interaction-based decision models with distributed knowledge sources enabling adaptive and more responsive decision structures.
C2. Distributed control systems	Systems with low level of autonomy among partners, such as job shop scheduling, where global objective functions are typically given.	Allow the parties associated with a system to negotiate for their tasks and their benefits with some degree of autonomy.	Systems integration with higher level of autonomy, such as supply networks.
C3. Collaborative problem-solving	Methods and quality of solutions to understand, define, and solve problems.	Information exchange to influence other parties' local decisions to act coherently and achieve better results for an entire organization.	Consider collaboration among loosely-coupled entities where less mutual benefits are acceptable or expected by collaborators.
D. Active middleware			
D1. Technology	Middleware, a layer of services below the application and above the operating system and network layer, operates to foster application portability and distributed interoperability, and provides active services to the clients of a system.	Facilitating the development of distributed applications among heterogeneous, legacy and advanced environments.	A very large scale computing platform serving highly heterogeneous, autonomous, and distributed components, beyond typical enterprise networks.
D2. GRID computing	Computing services that enable sharing, selection, and aggregation of a wide variety of geographically distributed computing resources, for solving large-scale and data intensive computing applications.	Computational economy and the development of grid computing architecture and its components, such as scheduler and resource allocator.	Explore the potential of grid computing paradigm in both scientific and business applications (e.g., supply grid, grid optimization).
D3. Distributed knowledge systems	Techniques and standards to design distributed information and knowledge systems, e.g., search robots, semantic webs, coordinate the distributed operation, provide security and access to millions of sources with wide variety of information.	Maintain high reliability, integrity, and quality of service for large scale distributed information and knowledge networks.	Better understanding of e-Trust among distributed information producers and consumers.
D4. Knowledge based systems (KBS)	Knowledge-based techniques to support human decision making, planning, learning, and action.	Construction and extraction of knowledge for variety of information needs.	Integration with other technologies to assist a human user or group of users in making better decisions, especially for complex, unstructured problems involving high levels of uncertainty.

Table 4. PRISM Center development of e-Work theories, models, and tools (examples).

e-Work design feature	'Role model'	Production application	Tool/model	Ref.
• Workflow and coordination	Distributed database	Computer integrated mfg.	• DAFNet & AIMIS	Kim (1996)
	Data flow	Aerospace mfg.		Sauvaire *et al.* (1998)
	Object orientation	Laser machining cell		Lenart (1993)
• Information sharing and collaboration	Task graphs	Distributed designers	• IDM	Khanna *et al.* (1998)
	Network computing	Distributed teams	• Co-X Tools	Eberts and Nof (1995)
	Internet/intranet	Supply networks	• Shared Process	Park (2002)
	Internet	Construction supply chain	• Rebar Portal	Castro (2003)
	Internet/intranet	Production and sales	• T-C-M	Matsui *et al.* (2003)
• Collaboration planning	Resource planning	Multirobotic assembly	• CRP	Rajan (1993)
• Agent design	Agent theory	Manufacturing operations	• ABMS	Huang (1995)
• Collaboration protocol design	Telecom. Protocols	ERP applications	• TIE/P	Anussornnitisarn (2003)
	Adaptive control	Electronics testing	• TestLAN/a	Williams *et al.* (2002)
• Middleware protocols	Client-servers	Automotive electronics	• RAP	Esfarjani (1994)
		Assembly	• TOP	Peralta (1996)
• Parallelism	Parallel computing	Global shoe design & mfg.	• DPIEM	Ceroni (1999)
• Resource and task allocation	Local area networks	Electronics assembly & test	• TestLAN	Williams (1994, 1999)
	Internet	Global automotive supply	• M.E.N. Method	Chen (2002)
• Synchronize / re-synchronize	Agent theory	Robotic maintenance	• ServSim	Auer (2000)
• Information assurance	Total quality	Agent-based mfg.	• (MERP)	Bellocci (2001)
• Fault tolerant integration	Sensor fusion	Flow MEMS sensors	• FTTP	Liu (2001)
• Error recovery	Computer recovery	Robotic assembly	• NEFUSER	Avila-Soria (1999)
• Conflict resolution	Telecom	Facility design by a team	• FDL/CR	Lara (1999)
• Multi-enterprise optimization	Network flow	Distributed enterprises	• M.E.N. Opt.	Chen (2002)
• e-learning	Learning theory	ERP applications	• (MERP)	Chen *et al.* (2001)
• Organizational learning	Enterprise computing	Manufacturing/assembly corp.	• CMS	Prytz *et al.* (1995)
• Viability measures	Artificial life	Human–robot facilities	• TIE/A	Huang (1999)
• e-work scalability	Distributed computer	Supply networks	• M.E.N. Model	Chen (2002)

ABMS: Agent Based Management System; AIMIS: Agent Interaction Management System; CMS: Corporate Memory System; Co-X: Collaborative Tool for Function X; CRP: Collaboration Requirements Planning; DAFNet: Data Activity Flow Network; DPIEM: Distributed Parallel Integration Evaluation Method; FDL/CR: Facility Design Language/Conflict Resolution; FTTP: Fault-Tolerance Time-Out Protocol; IDM: Iterative Design Model; M.E.N.: Multi-Enterprise Network; MERP: ERP e-Learning by MBE Simulations; NEFUSER: Neuro-Fuzzy Systems for Error Recovery; RAP: Resource Allocation Protocol; ServSim: Maintenance Service simulator; TestLAN: Testers Local Area Network; TIE/A: Teamwork Integration Evaluator/Agent; TIE/P: Teamwork Integration Evaluator/Protocol; T-C-M: Two-Center Model; TOP: Time-Out Protocol.

As shown in the table 4, dimensions of e-Work appearing in table 3 have been addressed for various application areas in manufacturing, production, and service. These efforts have been inspired by 'role models' from successful, proven models of distributed and parallel computing. The theories, models, and tools that have been developed and implemented are described in detail in the given references. Each of the projects has resulted with recommended design principles for effective e-Work (Nof 2002). Several key design principles, based on observations about the new needs and solution approaches, are summarized below.

8.1. *The principle of cooperation requirement planning, CRP (by Rajan and Nof)*

One of the most powerful augmentations of work abilities by e-Work is in the area of collaboration. Cooperation and collaboration vary from minimal information sharing and exchange, to fully collaborative enterprises (see definitions of cooperation, collaboration, interaction, and integration modes in Nof 1994). Usually, collaborative e-Work implies that the parties maintain collaborative autonomy, but must follow, jointly, certain common rules and fulfil certain service agreements (contracts). The main IT 'mechanisms' to enable cooperation and collaboration have been identified earlier in this article. They include agents, protocols, workflow and middleware, among others. *Active* protocols and *active* middleware, with agents that can perform their tasks autonomously and with local initiative, are preferred. But effective collaboration requires advanced planning (Rajan and Nof 1996a, b). Examples of planning issues are: How, when, and to whom can tasks be allocated and assigned to accomplish the given system's goals, subject to flow and synchronization constraints? How can pre-assigned tasks be re-assigned to solve real-time delays or errors? What level of agent autonomy is desired? When is a local initiative useful, and what, if any, central authorization is required?

The *Principle of Cooperation Requirement Planning*, CRP, includes two phases (Rajan and Nof 1996a, b). In the first phase CRP-I, a plan of 'who does what, how, and when', is generated based on the work objectives and available facility resources. In the second Phase, CRP-II, during execution, the plan is revised in real time, adapted to temporal and spatial changes and constraints. The adaptation responds to changes and new constraints both in the internal facility and its components, and in the external design, logistics and market interactions. A recent effort in robotic assembly and disassembly has been to integrate CRP with error diagnostics, recovery, and conflict resolution, as shown in figure 6 (Nof and Chen 2003). The principle indicates that effective e-Work requires both advanced and adaptive, real-time planning of the necessary cooperation and collaboration.

8.1.1. *Robotics and e-Work*

It is interesting to note the link between *robotics* and *e-Work*. Both terms originate from 'work'. The intelligence level of both relies on information and communication technologies. Robotics is a subset of e-Work, in the sense that robotic devices, including intelligent sensors, can work completely autonomously. An overall trend in smart robotic teams – normal size, micro, and nano robots – is their ability to interact (by programmed and optimal control) even better than human teams. A design challenge in robotic teams is to achieve optimized coordination of e-Work interactions as a key to effectiveness and competitiveness. CRP approaches will need to be extended to enable the design of solutions for the cooperation and collaboration expectations.

8.2. *The principle of e-Work parallelism (by Ceroni and Nof)*

Every model of e-Work implies interactions among software work-spaces and human work-spaces. The *principle of e-Work parallelism* (Ceroni and Nof 1997, 1999, 2001, 2003) is concerned with how to optimally exploit the fact that work in these respective spaces can, and must be allowed to advance in parallel (see table 5). In other words, to be effective e-Work systems cannot be constrained by linear (sequential) precedence of tasks. For example, tasks can be performed in parallel by software agents preparing information for human decision makers, while the latter are busy with other tasks, away, or asleep.

Scheduling, sequencing, and ordering work activities in parallel has long been known as a fundamental 'methods improvement' principle. In e-Work, workflow parallelism has a deeper meaning, since work activities can be widely distributed, locationally and over human- and software-spaces; there can be widely (and in effective e-Work also wisely) distributed human–human interactions; human–machine and human–computer interactions; and machine–machine, computer–computer interactions. The analogy between distributed computing, and e-Work in parallel interactions and networked organizations of teams and facilities, is depicted in table 5. This analogy has served well to understand the similarity and

Table 5. Analogy of e-Work with parallel and distributed computing. (following Khanna *et al.*1998; Anussornnitisarn and Nof 2000).

Analogy issue	Parallel / distributed / GRID computing	e-Work organization
Cases (examples)	nCube SGI Origin 2000 Computer GRID	Sensor array Mobile robot team Business enterprise Supply network/grid
Challenges	Routing Data transfer Task allocation Information security	Resource allocation Information exchange Task sharing Information assurance
'Atomic' unit	CPU node	Intelligent robot or sensor Internet-designer team ERP and CRM users
Communication infrastructure	Coupled or decoupled Communication processors	Communication bus; telecom. network; Internet/intranet/extranet
Interaction	Parallel computer O.S. GRID/Network O.S.	Competitive, cooperative, or collaborative
Models	Graph models; Message passing interface (MPI)	Network simulation; Parallel/distributed simulation

differences, and has led to the development of the TIE/X simulators, which are described later in this section.

8.2.1. *'KISS': Keep It Simple System!*

The essence of the 'KISS' is that the computer and communication support system can be designed as complex as necessary, as long as it can work autonomously, in parallel to and supportive of humans, subject to their inputs and instructions. The principle of e-Work parallelism identifies that to be effective, e-Work systems cannot be constrained by linear (sequential) precedence of tasks, unless they are dictated by dependency constraints. 'KISS' is associated with the principle of e-Work parallelism by the notion that new versions and advanced functions of software systems must minimize the need for repeated human retraining, by using internal, parallel e-Learning functions to simplify the transition to the evolving system's interfaces and logic.

8.2.2. *Change of work logic*

Just as computer software programs, e.g. sorting, in order to be effective do not and should not mirror the logic of humans (although they are clearly the product of human software developers) so can e-Work not replicate traditional human work procedures. The objective is clearly to augment human work abilities by new types of nonlinear (nonsequential) work models; attempt to execute in parallel whatever tasks that can be executed without violating dependency conditions. As an example, consider the assembly-and-test model, TestLAN (figure 5). Instead of having assembly workers (workstations) retain exclusive control of a shared tester while repairing diagnosed faults, a well-design task administration protocol with access to current information about the assembly design, repair probabilities and time distributions, can optimize the tester sharing among multiple, networked workstations.

8.2.3. *'Multiple heads'*

Major challenges of e-Work stem from the power of modern IT: The information overload becomes larger and the rate at which it is reaching us is faster ('higher velocity'). But the individual human brain cannot (yet) cope with the ever increasing overload and communication rates. Many humans 'put their heads together' to develop management and operational information systems (such as ERP, CRM, etc.), and increasingly, the expectation that a single person must contend with those information systems during e-Work is unreasonable, or at least requires intensive training (Huang and Nof 1998).

8.2.4. *Distributed planning of integrated execution method, DPIEM*

DPIEM is a method for planning how to satisfy a CRP-based plan (Ceroni 1996; 1999). A key issue related to such planning under the e-Work parallelism principle is the ability to determine the optimal Degree Of Parallelism (DOP). DOP is defined as the maximum level of resource and task parallelism, which will balance the trade-off between increased communication, transportation, and equipment costs incurred with a higher DOP, and the increased yield (productivity) gained by that level of parallelism.

In addition to the issue of DOP, there are several basic issues in the design and implementation of any coordinated problem-solving and decision support system for e-Work, which can also be considered as key issues in active middleware development. The principle of e-Work parallelism includes five guidelines, seeking to let the e-Work Support System (EWSS):

(1) Formulate, decompose, and allocate problems; synthesize results among groups of independent entities (resources, processors) and the humans operating and managing them.
(2) Enable applications to communicate and interact; the design issue is to determine under which task administration protocols, what, and when to communicate during the e-Work.
(3) Trigger and resynchronize independent entities to act coherently in making decisions and taking action; the design issue is to determine *which* decisions and actions can be assigned and delegated to humans or to machines, and *to which* humans and machines.
(4) Enable entities to reason about actions, plans, and knowledge of other agents (humans and machines), and coordinate with them.
(5) Develop conflict resolution, error recovery, diagnostics and prevention: recognize and reconcile disparate viewpoints and conflicting intentions among independent entities. (This issue is discussed further under Principle 3 below.)

For instance, PIEM (with centralized optimization algorithms) and DPIEM (optimization with distributed protocols) were developed for evaluating and planning the communication and coordination trade-offs in e-Work with parallelism in design, manufacturing, supply, and sales functions by Japanese, North American and South American companies; for outsourcing strategies;

information systems middleware development; and for robotic cells design. (Papastavrou and Nof 1996, Nof and Huang 1999, Auer *et al*. 2000, Auer and Nof 2000, Lara *et al*. 2000, Ceroni and Nof 2001, Nof 2000a, 2003a, b.)

8.2.5. *The Co-X tools*

Another example of the principle of parallelism are the Co-X tools (developed by Eberts and Nof 1993, 1995), where 'Co-' implies coordinated, cooperative, and/or collaborative support tools, e.g. Co-design, Co-plan, Co-storm (for collaborative, creative brain-storming), etc. The details of 'Co-' can be designed at three levels of interaction and collaboration:

- Level 1 – Interfaced sharing of information, ideas, and plans.
- Level 2 – Parallelism of information processing tasks and of physical tasks.
- Level 3 – Beyond Level 2, addition of active protocols and agents to support (optimize) better effectiveness through parallelism.

The Co-X tools have been developed and implemented for teaching and learning the benefits and limitations of different team designs, and for lab experiments to demonstrate and investigate the interface design and usability of collaboration support (EWSS) in e-Work.

8.3. *The principle of conflict resolution (by Huang and Nof)*

This principle addresses the cost of resolving conflicts among collaborating e-Workers. It has been observed and recognized that with a greater rate of interactions, which increases with the number of collaborating parties, there is also a greater occurrence of conflicts and errors. This problem is critical in terms of scalability. It means that beyond the information and task overloads, e-Work must be designed to overcome quickly and inexpensively as many errors and conflicts as required to be effective. To illustrate this issue, suppose: q is the relative portion of human intervention in the resolution process; s is the probability of resolving a conflict in any one iteration of negotiations. Huang and Nof (1999a) showed that for practical values of s, the resolution cost would depend on q as follows:

(a) With higher q, i.e. more human interaction and involvement are needed, the cost of resolution grows exponentially and it is unbounded. Implication: Under this design conditions, the e-Work system will collapse because of ineffectiveness.

(b) With a smaller value of q, approaching zero, meaning IT services are designed and applied for resolution-support by automating functions of negotiations for corrections or compromises, then the total cost of resolution reaches an upper bound. Implication: In this case, e-Work systems can be effective.

The design objective, following this principle, is to develop better and more powerful IT support (bringing the value of q to a minimum) for detection, prevention, and resolution or recovery of errors and conflicts, leading to lower overall costs, better quality results, and more effective e-Work. Further details are explained by Huang *et al*. (2000); Anussornnitisarn and Nof (2003).

Conflict resolution for collaborative facility design by FDL/CR was developed by Lara (1999), Lara and Nof (1999a, b, 2003) and knowledge-based diagnostics and recovery by NEFUSER were developed by Avila-Soria and Nof (2000) (see table 4). For example, FDL/CR encompasses rational execution of pre-ordered conflict resolution approaches, from the simpler and least costly, to the more complex and costly resolution mechanisms: beginning with support for direct negotiations; if that stage fails, moving to third-party mediation; then incorporating additional parties; if still not resolved, moving on to persuasion; and if all else fails, applying support for arbitration. This method incorporates principles for prevention of conflict perpetuation and escalation to improve short-term performance, and computer-based learning to improve usefulness and effectiveness of future resolution tasks. To incorporate prevention principles, the last stage of the method, arbitration, is sequentially organized in three phases of conflict modelling and analysis:

(1) Incorporation of principles for prevention of conflict perpetuation and escalation, to improve the detection, resolution, and consequently, the e-Work performance;
(2) implementation of computer-based learning, to increase the usefulness of the resolution-support method; and
(3) integration of conflict detection and resolution, which results in an increased effectiveness, and potentially better quality of the facility design.

Control Protocols for the diagnostics, prevention, resolution, and recovery of errors and conflicts are important design issues. Future collaborative e-Work, including robotics and teamwork, will depend on cheaper, redundant groups, arrays, networks, and grids of interacting parties, e.g. business partners, human designer teams, human–robot task forces for security and rescue operations, and DNA-sensor arrays. Enabling effective e-Work in each of these examples will require effective handling of errors and conflicts.

8.4. *New measures and evaluation*

New work models, as those illustrated in table 4 for the design of effective e-Work, require new measures in addition to traditional measures of effectiveness. Some of the measures have already emerged with the advent of CIM and networked enterprises: Flexibility, agility, connectivity, integration-ability, scalability, reachability, and so on. Two recent measures of particular interest to e-Work design are level of autonomy, and viability (e.g. Huang 1999).

The level **of autonomy** relates to the delegation of authority, decentralization, and to how *active* the agents, protocols, and other e-Work system participants can be. **Viability** in the context of e-Work (e.g. of the whole e-Work system, or of its components) has been defined as a relative measure of the ratio between the cost of operating and sustaining agents, and the rewards from their services. Theories of agent design and agent interaction models have been developed using measures of autonomy and viability (Huang and Nof 1999b, c). Recently, Anussornnitisarn (2003) has discovered that e-Work rationalized by viability-based protocols performs significantly better than by protocols ignoring the viability measures. Examples of other measures emerging as useful for e-Work design are learning-ability, collaboration-ability; and related to errors and conflicts, interesting measures are prevention-ability, detect-ability, diagnosis-ability, and recovery-ability. A critical area to e-Work is information assurance, including measures of security, integrity, and information significance (Bellocci 2001, Bellocci *et al.* 2003).

Combinations of O.R. and A.I. models and simulation have been developed to measure, understand, evaluate, design and plan e-Work systems. Exploiting the analogy between e-Work systems, and parallel and networked computing, (see table 5), a family of parallel simulators, TIE/X has been developed and implemented (Anussornnitisarn and Nof 2000). These simulators (figures 4 and 8) can assign autonomous CPUs to repre-

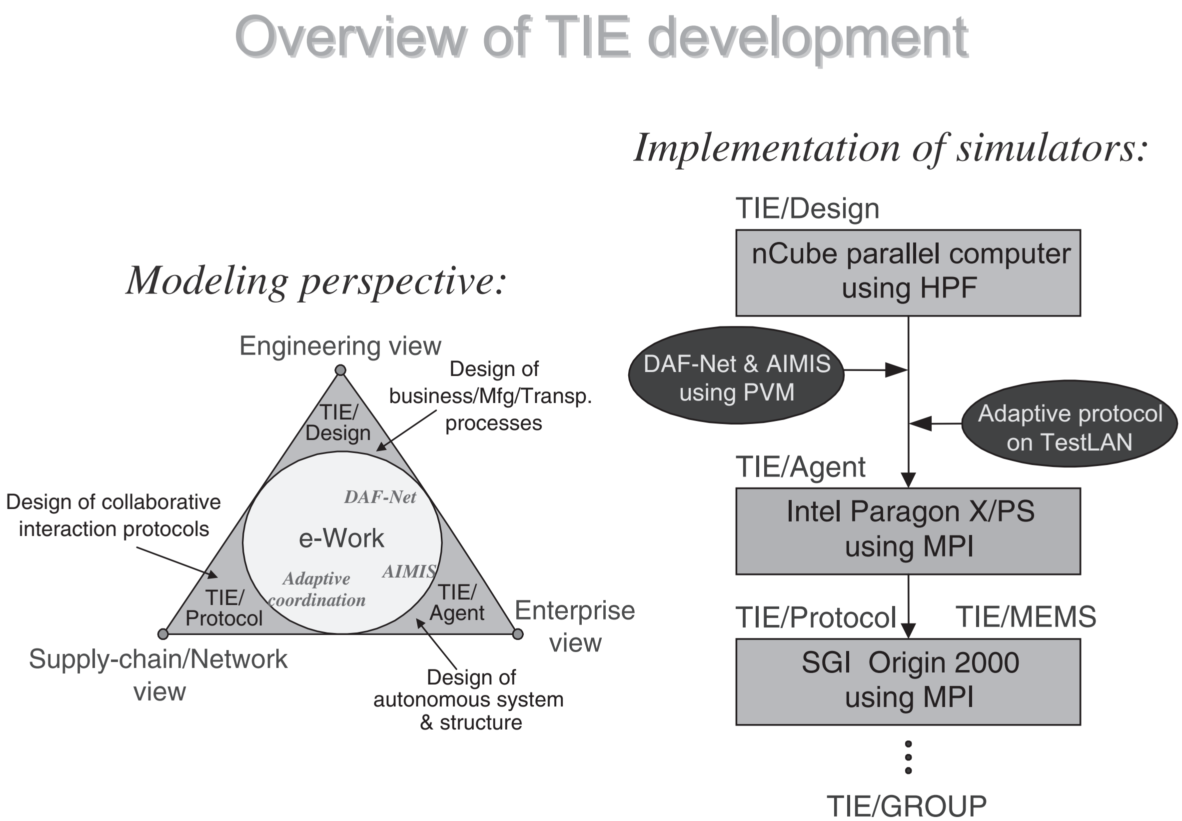

Figure 8. The Teamwork Integration Evaluator (TIE). TIE's purpose: use the analogy of parallel/ distributed/ networked computers to model e-Work environments – networked designers; agents; protocols; sensor arrays; autonomous groups (Sponsors of TIE development include NSF, IBM, Caterpillar, SGI, TAP, Tecnomatix, and Indiana 21st Century Fund for Science Technology.) Note: Tools and models mentioned in this figure are listed in table 4.

sent each participating entity in an e-Work team, observe their interactions under given task administration protocols, and generate performance evaluation measures to help the designers of alternative e-Work systems.

9. Conclusions and future challenges

The way people and systems operate, work, communicate, and collaborate is being transformed by e-Work. Hence, understanding how to design effective e-Work is fundamental to productivity and competitiveness. Models of e-Work have been developed to address design issues, from interaction to coordination, conflict resolution and error recovery, and the management of complex e-Work production and service environments. Design and decision tools and methods have been developed for this modelling, with the objective of understanding the emerging requirements, limitations, and potential capabilities of e-Work. Modelling challenges for e-Work design include enhancements of models, such as TIE/X, to include further e-Work functions along the 15 e-dimensions in table 3, which depend on emerging Internet, Intranet, and related technologies. Other challenges include the evaluation and assessment of new measures, mentioned in the previous section, such as collaboration-ability, conflict prevention-ability, and error detection-ability.

Based on extensive studies of e-Work systems, discoveries of several design principles have been discussed in four main areas:

- Cooperation requirement planning
- e-Work parallelism
- Error and conflict handling
- e-Work effectiveness measures.

Effective e-Work is fundamental to e-activities, such as e-Commerce, e-Business, e-Learning, intelligent transportation, and e-Manufacturing. Enabling services to decouple applications from the computer and communication layers can augment human work significantly by performing many tasks in parallel, by software and hardware agents, thus reducing the information overload and task overload currently imposed on human workers. In the next generation of e-Work, based on evolving IT, systems will be developed with inherent collaborative support tools in large-scale e-Work environments.

Several open questions remain: Will people like to work in the collaborative e-environment? Will workers and managers be willing to trust the results obtained and delivered by the agents' work? Will they accept computer-supported negotiations? The design of effective e-Work will also have to address these issues.

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