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Intelligent Manufacturing Systems in Global Manufacturing Paradigm: a critical review and new research issues

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Abstract: In this paper, a review of recent developments in Intelligent Manufacturing System (IMS) is presented. The discussions proceed in five aspects: organisational structure of IMS, management/control of the operation of IMS, design methodology for IMS, computer aided design of IMS, and infrastructure development for IMS. These aspects together cover the domain of IMS research and development. Based on the critical review of previous IMS work, new research issues and possible methodologies are identified. Some preliminary results, generated from a project being carried out at the Department of Manufacturing Engineering and Engineering Management of City University of Hong Kong, are also reported.

Keywords: Global manufacturing, Intelligent manufacturing system.

1. INTRODUCTION

The 1980s and 1990s have seen the emergence of new philosophies of business processing and management for manufacture industry in response to the ever increasing demands from customers and global competition. The trends towards globalisation of market and of production of goods and services, and towards outsourcing have resulted in a new paradigm for manufacturing called *Global Manufacturing* (GM). Manufacturing enterprises in this new paradigm are acquiring characteristics such as activity-globalisation, customer-orientation, and multiple-organisation-collaboration. The aim of this paper is to review some of the more important issues concerning the development of the so called *Intelligent Manufacturing Systems* (IMS) in the global manufacturing paradigm, and to identify potential new research issues and methodologies. We begin the review with a brief explanation of the important concepts.

1.1 Intelligent Manufacturing System

The development of intelligent manufacturing systems has gained tremendous interest in recent years, although the term *intelligent* is yet to be fully defined. Albus[1] defines intelligence as the ability of a system to act appropriately in an uncertain environment to increase the probability of success of the system given the criteria of success. Suh[2] considers intelligence to be the ability of the manufacturing system to reconfigure the production system, including machines, purchasing, inventory control, and factory layout, in response to changing market demands for various types of products. IMS was initiated by Yoshikawa in 1989, who stated[3]: "The intelligent manufacturing system takes intellectual activities in manufacturing and uses them to better harmonise human beings and intelligent machines. Integrating the entire corporation, from marketing through design, production and distribution, in a flexible manner which improves productivity. "

In this paper, we will largely adopt Suh's definition and extend it into a global manufacturing paradigm. In the context of GM, the physical realisation of IMS is a temporary assembly of globally distributed autonomous production/management units linked primarily by the goal of profitably serving specific customers and operating in an environment of abrupt, often unpredictable changes. Therefore, intelligence must also refer to the abilities to operate autonomously and co-operatively, to be rapidly adaptable to continuous changes both in markets and technologies, and to be flexible throughout its organisational structure and processes.

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Furthermore, in this paper, we will consider intelligent manufacturing system as covering all aspects of new manufacturing concepts, like agile manufacturing, lean production, JIT, CE, virtual corporation, etc., in the sense of acting appropriately to succeed in an uncertain environment. The term *manufacturing system* here will be made interchangeable with terms such as *production system* (mostly used in Europe), *manufacturing enterprise* and *organisation* (in organisational view).

1.2 Five Aspects to be Examined

A preliminary study has led us to believe that the following five aspects are fundamental:

- *Organisational structure* of IMS.
- *Management/control of the operations* of IMS.
- *Infrastructure development* for IMS.
- *Design methodology* for IMS.
- *Computer Aided Design* of IMS.

The first three aspects are about IMS itself. The structure of IMS is about components and their connections at various levels and views; the second aspect concerns the behaviour of IMS; the third aspect addresses the infrastructure under which an IMS can behave as such. The third aspect may be embodied by the first aspect, as the problem of infrastructure is relevant to communication between various components in an IMS. We separate them for the reason that the issues concerned in the third aspect do not necessarily preclude issues related to the first aspect. The last two aspects are obviously about design or redesign of an IMS system.

1.3 The Organisation of the Paper

In sections 2-6, we will discuss these five aspects respectively. In section 7, progress of an on-going project at the Department of Manufacturing Engineering and Engineering Management of City University of Hong Kong will be briefly reported. Section 8 concludes the paper with a summary of the new research issues, objectives, and possible methodologies identified through the project.

2. ORGANISATIONAL STRUCTURE OF IMS

Organisational structure is needed to constitute a system in a sensible order. It describes the functional responsibilities of individuals with regard to resources, information and execution. In other words, it focuses on issues such as roles, authority, empowerment. A clear definition of organisational units and a specification of authority-responsibility-accountability relationships are depicted within the organisational structure. The organisational structure is not only limited to people but also equipment; both people and equipment are considered as system components.

The main characteristics of the traditional pyramid shaped organisational structure include centralisation in control and decision-making, steep hierarchies, and horizontal and vertical over-the-wall division of labour. As a consequence, these structures maintain clear boundaries between functional departments and separate the tasks of work planning and design from those of work execution. Specific organisational units, separate functions and clear relationships, makes it easier to represent all aspects of inner structure of an organisation explicitly and completely.

It is understood that the organisational structure of IMS in a global manufacturing paradigm must be different from the traditional ones. New philosophies are needed to guide the business of IMS such as total customer focus, corporate structure, team work, empowered workers, facilitator/coach type of managerial behaviour, and decentralisation of control. Some new types of relationships/constraints (inter-organisation structure) must be identified between the manufacturing units which may be geographically different as well as different under separate management contexts. All these make the IMS organisational structure more complex.

Rood[8] notes two forms of organisational structure: formal and informal. Both forms play major roles in the effectiveness of the enterprise. The formal structure is an intentional location and arrangement of enterprise functions based on demands of the work, tradition, technological constraints, etc. It determines the official distribution of authority, responsibility, accountability, roles, and functions. The informal structure is unintentional and not formally prescribed. It emerges as an ad hoc form of working groups, with the informal power structure being developed and decisions being made and carried out without formal authority. Rood[8] has acknowledged the presence of informal structures, but has not explored the underlying principles that guide the development of such informal structure.

Fox *et al*[9] explores an organisation ontology for the TOVE project[10]. The Ontology views organisations as composed of agents playing roles aimed at achieving specific goals according to various constraints defining "rules of game". The ontology puts forward a number of conceptualisations for modelling organisations: agents, roles, positions, goals, communication, authority, commitment, and thus can provide declarative semantics for the system with shared nature. Their efforts have focused on supply chain management.

These studies have laid foundations in the sense of suggesting a framework for the organisational structure of IMS. However little attention has been paid to developing tools that facilitate a systematic analysis of the impacts of organisation structure changes on team/system behaviour and performance. In fact, the organisational structure itself seems to lack systematic representations in depth.

3. MANAGEMENT AND CONTROL OF OPERATIONS OF IMS

The management and control of IMS involve a variety of activity/process planning, co-ordinating and control functions that are carried out in an IMS so that the system behaves in such a manner as to ensure business success within the given management/control strategies.

An emphasis on system intelligent behaviour, as previously described, leads to some changes in operations in an IMS. For example, business transforms from the bureaucratic "command and control" mind-set of the past to a "consensus and consent" system of values appropriate for a fast-changing environment, i.e. encouragement of co-operation and collaboration of people with processes is the most important task in such a situation. Customer-orientation shifts the focus of manufacturing enterprises from the control of resources to a customer-centred control of time. Pursuit of quality moves to the pursuit of complete customer satisfaction. The globalisation of production resources increases manufacturing enterprises' reliance on subcontractors and suppliers. The management of value-added partnership networks, i.e., supply chain management, is therefore a major challenge. In short, the conventional site-oriented production planning and control concept migrates towards a multi-site co-ordination and site control concept with considerable decision autonomy given to the distributed virtual organisational units. This has resulted in the emergence of two new techniques — distributed project co-ordination and distributed manufacturing control.

3.1 Project Co-ordination

Project co-ordination concerns higher level manufacturing activities in an IMS. It includes[11] the planning, scheduling and execution of projects, co-ordination of tasks, resolution of competing objectives, achievement of global coherence, change propagation, communication across heterogeneous groups, and maintenance of access to valid information. Traditional production planning and controlling approaches no longer suit the IMS situation. Production of a product at manufacturing units which site in geographically and politically different regions and under different management boards essentially calls for the application of project management science and technology. Note that project management science and technology are already being used in the production management of One-Kind-of-Product (OKP) products (such as construction). Many studies have described the aspects of project co-ordination, such as co-ordination of tasks[12], communication and change propagation[13], and software to support project management and co-ordination of people[14].

Maurer[15] presents an integrated project planning and execution environment called CoMo-Kit. It consists of three main parts: the Modeler which allows to plan a project, the Scheduler which supports the execution of a project and manages the information produced, and the Information Assistant which allows access to the current state of a project. The approach allows interlocking of planning and execution. Starting with an initial plan the first tasks are executed. Based on the results, the plan is refined and/or extended. Such a workflow engine provides more flexibility than conventional workflow approaches. This system uses project plans to generate causal dependencies between information entities and thereby improves the traceability. Because of improved traceability, CoMo-Kit is able to support reaction to changes. Because it assumes that the information produced causally depends on the information used, it cannot handle dependencies between decisions which are not directed. A more comprehensive project management model is Goldmann's Procura system[16], which supports the planning and scheduling of agent based design projects in a hierarchical, top-down approach. This tool uses Charles Petrie's REDUX' system[17] to enable the re-planning and revision of planning/scheduling decisions. Future work on Procura will include automating scheduling while introducing the aspects of negotiation, organisational structure between the agents involved in the planning and execution process, and limits on the authority of individual agents to planning and/or doing specific tasks.

3.2 Distributed Manufacturing Control

Distributed manufacturing control handles lower level manufacturing activities in an IMS. Its major role in supporting the operation of an IMS is to manage and control material and information flows relating to the physical manufacturing operations which may be widely distributed geographically and yet closely linked. Distributed manufacturing control may refer to shop floor control in conventional integrated manufacture.

A generic Mediator architecture for distributed task planning and co-ordination has been developed using multi-agent paradigms[18]. This architecture dynamically structures heterogeneous agent environments into well-organised clusters, in which co-ordination activities take place. Agents are associated dynamically within the clusters according to their functional capabilities and availability. Within a cluster, the problem-solving activities are carried out through collaborative transaction. This architecture provides two key capabilities: integration of activities across heterogeneous environments, and real-time self-adaptation of the Mediator structure to environmental changes. A demonstration of application of the mediator architecture and related mechanisms in dynamic scheduling of product lots in an intelligent manufacturing system is also presented in[18].

4. DESIGN METHODOLOGY FOR IMS

There are a number of distinct methodologies, e.g., SADT, IDEF, GRAI, and CIM-OSA which could be explored to design or redesign an IMS. The first three methods offer a means of representing manufacturing activities in a flowchart form in order to analyse any deficiencies within the existing system, but offer few guidelines for the system designer to overcome deficiencies, i.e., redesign. CIM-OSA attempts to provide generic building blocks to enable the development of CIM systems. However there are few insights into the process of system design. These methodologies concentrate predominantly on the design of internal systems without a consideration of the virtual enterprise concept.

The initial setting up of the configuration of an IMS must take cognizance of the requirements on development of a product with production batch size being possible only one (OKP). Further the initial design may have to be periodically modified due to changes on various aspects such as unsatisfactory performance of a partner factory or supplier which may lead to a overall failure of the product development. In the context of IMS, such issues are called partnership synthesis/decoupling.

The FOF (Factory of the Future) project aims at developing a designer workbench[20,21] for OKP systems. The approach uses a conceptual model of the enterprise that relates design choices (DCs) to performance indicators (PIs), called DC-PI network. The idea is that a relationship exists between each design choice and its relevant performance indicators. These relationships, obtained from theoretical or empirical knowledge, are expressed in models. When design choices are changed, the effect on the system is measured by the performance indicators. Design choices may be related to products, resources (people, facilities, equipment), and systems/organisations. Examples of performance indicators are total profitability, throughput time, inventory level, reject rate, and number of customer complaints. The FOF aims at an integration of various scientific disciplines involved in the design of production systems into one global conceptual model. One of the FOF products is a tool called REMBRANDT[21], the REference Model Browser And Design Tool, which is used to represent a DC-PI network. However, in general, FOF still remains a theoretical framework which needs to be developed further[20].

Assuming that the design of an IMS based on Virtual Enterprise (VE) concept is similar to design of a machine system, Zhang[22] proposes a general design process model (see Fig.1) for a VE system in the light of general design theory developed by Yoshikawa[23]. Zhang[22] recognises that in machine design we only have required functions, constraints and wishes, while in VE system design, products that the VE system produces are an equally important requirement. Type synthesis in machine design corresponds to selection of component types, while in VE system design, types of components could not only include a factory own equipment but also partner factories'. Instance synthesis corresponds to finding the most appropriate components for a particular type of component. Configuration synthesis is unique in VE system design, which takes into account factors such as geographical location of a partner factory specified after the instance synthesis. Activity feedback has three main implications. *Firstly*, feedback from the type synthesis to the requirement analysis may imply that a prescribed product structure will not possibly be implemented with the current state of the art of manufacturing technologies done by any partner factories. Therefore request a variation of the preceding decision on the product structure is required. *Secondly*, the feedback from the instance synthesis to the type synthesis as well as the requirement analysis may imply that no partner factory has been found to commit itself to the production or delivery of a portion of the product due to the limits of time, quality, quantity or cost. This calls for reactivating the type synthesis or requirement analysis which could render to an alternative product structure. *Thirdly*, the feedback from the configuration synthesis to the instance synthesis and the preceding activities may imply that the geographical difference of a partner factory could bring some product transportation problems. The presence of the activity feedback also implies that a simultaneous decision process may be needed in pursuit of the global optimisation of a VE system design. This work is still on-going.

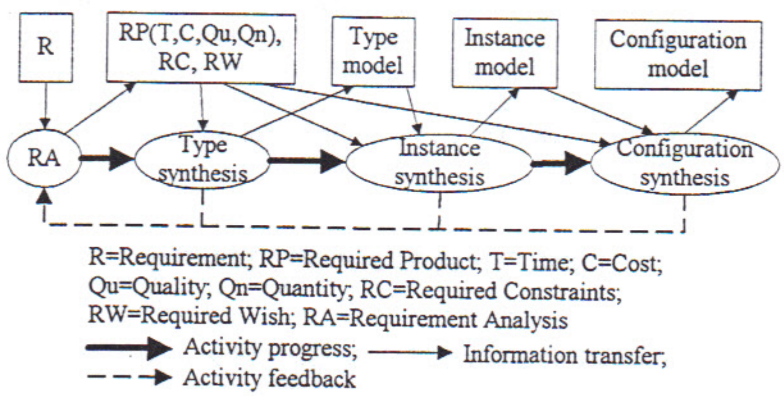

Fig 1. General Design Theory for IMS Design

Assuming an initial configuration has been created, how to organise those dispersed systems into a virtual closely linked organisation becomes a most important issue. From an organisational design point of view, the following questions must be addressed[25, 26] to achieve a successful design of IMS:

- *Formation of organisational units and task arrangement*: What are the basic organisational primitives? How to organise (group) them into units? Should tasks be arranged more concurrently or sequentially? What will be the consequence of the introduction of more concurrency? Who should be responsible for each task? How are tasks interrelated with each other? How do these relations affect relations between the responsible actors?

- *Control structure and policy*: What kind of control structure should be implemented? Should it be more hierarchical or flatter? Who should report to whom? Given a control structure, what decisions should be made at which level of the hierarchy?

- *Communication structure and policy*: Who can talk to whom? Who should talk to whom about what? Should the team have formal meetings frequently? Who should attend each meeting? Could team members meet or talk to each other informally whenever they need?

Although the answers to some of these questions are straightforward when a specific task situation is given, answers to many of the questions are not so obvious. A methodology for organisation design is therefore needed. The generic steps for design of organisation can be identified[24] as: *requirement definition, synthesis, analysis, evaluation,* and *acceptance* or *recycling* based on the evaluation of performance. *Analysis* plays an important role in this process since it is the basis of *evaluation* and iterating *synthesis* for optimal design. Following this idea, Jin *et al* [25] have developed a computerised analysis tool to support the systematic design of organisation structure for concurrent engineering projects (Virtual Design Team — VDT). They adopt a model-based simulation approach. The system describes the design tasks, actors (i.e., designers and managers), and organisation structures as inputs, and produces the predicted records of the actors' design and co-ordination behaviour, project duration, cost, and design process quality as output. VDT has been successfully applied to more than ten realistic engineering projects. However it only covers engineering domain.

Wortmann[26] proposes a synthesised theoretical framework to support the design of production systems. The approach attempts to integrate three theoretical frameworks which respectively deal with: workflow through the production system, structure of the primary resources, and organisation of decision making. The basic idea is to extend and apply group technology to engineering all kinds of knowledge work.

5. COMPUTER AIDED DESIGN OF IMS

Since the design process of an IMS is complex, computer assistance to the designer of IMS in decision making is certainly helpful. Hence, a computational model of IMS is particularly needed. A computational model is computerised representation of IMS and the decision processes involved in the design/analysis of an IMS. Thus, it spans a wide spectrum of IMS.

Barbett *et al* [27] present a general object oriented business process model for the virtual enterprise. They propose that the enterprise' activities be the basic building blocks. However enterprise activities become useful only when organised into business processes which co-operate to produce desired enterprise results. In the context of this paper, business processes fall into three categories. Category (1) processes transform external constraints into an internal constraint structure that might be expressed as a system of objectives, policies, and procedures. Category (2) processes acquire and make ready resources used by the enterprise. Finally, category (3) processes transform the family of inputs into the desired enterprise results or outputs. A virtual enterprise consists of a set of business processes from category (1) which are collectively owned by the virtual enterprise and a set of business processes from all three categories (1,2,3) which are owned by two or more individual enterprises, but used by both the individual enterprises and the agile or virtual enterprise. The aim of this project is to assist companies desiring to enter into a virtual relationship by defining the functions and interfaces of critical business processes, thus allowing for a more rapid and efficient integration of the expertise which will be contributed by each partner in the virtual company. At the time of writing, however, the work is in progress and no detailed prescriptions are yet available.

In modelling the organisational behaviour of concurrent design teams[25], Jin *et al* adopt the premise that organisations are fundamentally information processing structures. In this view, an organisation is an information processing and communication system, structured to achieve a specific set of tasks, and composed of limited information processors termed "actors" - individuals or undifferentiated specialist sub-teams. Actors send and receive messages along specific lines of communication through communication tools. They pay attention to a selected message in their "in-tray" and spend a certain amount of time to process the message. Organisational structure is defined by a set of attributes of and relationships among actors. The authors differentiate between formal control structure and information communication structure. A formal control structure is a hierarchy of reporting-to (or supervise) relationships between the actors and has a certain level of centralisation. Reporting-to links guide actors to determine with whom they should communicate when task fails; and the level of centralisation determines at what level of the hierarchy a specific decision should be made. An informal communication structure is defined by coordinate-with relationships among the actors and has a certain level of formalization. Coordinate-with links specify who can talk to whom, and level of formalization determines the frequency of the communication. Through such a model-based simulation, the analysis and design of the organisation structure are carried out.

An enterprise model (EM) neither implies an attempt to build a "universal model" of an enterprise, nor is it capable of supporting all decision. EMs, connected to operating results, should give early warning of the need to reorganise, and reveal what needs fixing and how. It is our belief that the final decision concerning an IMS depends on the designer.

6. INFRASTRUCTURE DEVELOPMENT FOR IMS

So far, we have described the design and management techniques for IMS. Our aim in this section is to shift the emphasis to the information technology (IT) requied to support the implementation with the objective to integrate components of an IMS. Infrastructure provides a integration platform to support all computerised applications used in a distributed, heterogeneous manufacturing environment. The software side of infrastructure will be particularly emphasized.

From the information management point of view, the companies participative in an IMS should be able to share data as if they were one, well-integrated company. Thus electronically enabling virtual collocation in time and space is the major objective to achieve the enterprise integration. To achieve the integration objective, three sets of related problems must be addressed in infrastructure development:

- *Connectivity.* Flexible configuration and extension are enabled by adding new member applications
- *Interoperability.* Different applications on different platforms should be able to effectively and efficiently exchange information.
- *Security.* Data access classification mechanism has to be considered.

A detailed discussion of required functionality of information system for management of distributed production has been given by Hirsch[28]. The integration platform has to provide services which support the characteristics needed by IMS. First of all, to support integration of autonomous applications an integration platform has to be neutral to the subjects which are to be integrated. This means that the original functionality of the integrated components may not be influenced by the integrating system[28]. This is an essential principle, in our opinion, to guide the development of infrastructure.

Many efforts have been made on infrastructure development, viz., the National Industrial Information Infrastructure Protocols (NIIIP) project funded DARPA, the Rapid Prototyping of Application Specific Signal Processors (RASSP) program initiated by ARPA and US Department of Defence, and Global Engineering Network (GEN) supported by European Commission.

NIIIP's technical vision is to define ways for existing applications to inter-operate and to make the technologies fit together in a useful manner based on existing, emerging, and defacto standards. Its protocols provide an infrastructure for the inter-operation of commercial-off-the-shelf (COTS) products in the industrial domain. The protocols are being validated in a series of demonstrations. RASSP infrastructure efforts intend to dramatically improve the way complex embedded digital electronic systems, particularly embedded digital signal processor, are designed, manufactured, upgraded, and supported. GEN is actively involved in establishing a large scale engineering knowledge infrastructure as a basis for new and emerging collaborative work structures among the manufacturing community[29].

7. RESEARCH INTO GLOBAL MANUFACTURING SYSTEMS

This section will briefly introduce an ongoing project named Research into Global Manufacturing Systems (GM), being carried out at the Department of Manufacturing Engineering and Engineering Management of City University of Hong Kong. Our ultimate goal is to develop validated methodologies and computer support systems to support a factory to do their business based on the agile manufacturing concept. The general approach behind this project is to apply data modelling technology and general design theory and methodology applicable to machines. Some preliminary results have been achieved.

In the development of a generic conceptual data model of agile factories in global manufacturing paradigm[34], the impact of the agile factory concept on factory organisational structures have been studied. The agile factory system structure is explicitly represented by following the Function-Behaviour-Structure (FBS) paradigm, the core of the general design theory[23]. With regard to the representation semantics, agent systems paradigm has been taken for system representation, thereby a taxonomy of agile factory agents is proposed, with their structures, behaviours and functions. The structure of the agent includes the relationships/constraints being presented between agents. With regard to the representation method, we combine Object-Oriented (OO) modelling approach with an Object-Oriented Constrained (OOC) modelling approach[33]. Particular attention is given to the OOC approach which proposes that the constraint between objects be separately represented from objects. Finally we use EXPRESS to describe the FBS model of agile factories. This work addresses aspects 1, 4 and 5 listed in section 1.2.

A methodology for partner synthesis (see Fig.1), based on the application of the general design theory, and the architecture of a computer program system for partner synthesis based on the proposed methodology have been created[22]. A prototype system has been developed with Microsoft FoxPro for the implementation of the product database, the partner factory database, and the partner factory synthesis tool based on the Simple Attribute additive Weighting (SAW) decision theory[22]. This phase of work addresses aspects 4 and 5 (see section 1.2).

Zhang[32] identifies the need to develop an effective data model for millions of product variants that could result from IMS in the global manufacturing paradigm. The data model has to represent product families, product variant instances and project management information. It is possible that a "instance-as-type" problem occurs in the model which has potential to lead to data inconsistency. Solutions have been developed for this problem.

8. CONCLUSIONS

Five aspects concerning IMS have been identified. Some problems in the development of IMS in the global manufacturing paradigm have been discussed. Four research issuess have been identified. They are summarised below.

Issue 1: The understanding of the organisational structure of IMS in the global manufacturing paradigm needs to be further studied. There is a need to understand the new relationships/constraints between system components which could be (1) geographically different, (2) politically and culturally different, and (3) managerially different. There is also a need to study the life cycle or evolution of such relationships/constraints. The starting point to identify them is to study impacts of these differences on the performance of a manufacturing entity if only traditional management and control approaches are taken. A joint research team consisting of both manufacturing researchers, international business researchers and industrial practitioners should be helpful to this research.

Issue 2: The theory and methodology for management/control of an IMS in the global manufacturing paradigm needs to be further developed. Project management science needs to be employed with some possible modifications in managing design and production activities in an IMS. There is a need to identify the relationships/constraints between project management activities and shop floor management/control activities in order to run an IMS effectively.

Issue 3: The theory and methodology to design an IMS in the global manufacturing paradigm needs to be further developed. Traditional approaches to manufacturing systems design or redesign are basically limited to shop floor. There is a need to consider the complete enterprise by combining enterprise modelling/analysis and shop floor manufacturing systems design theory. A very promising methodology is to employ design theories such as Suh's axiomatic design theory and Yoshikawa's general design theory as well as tools in developing an IMS in global manufacturing paradigm. Following this line of thinking, we need to develop a knowledge base containing both knowledge from manufacturing engineering science and enterprise level business management science.

Issue 4: The degree of virtuality between system components needs to be studied with respect to a particular social and business environment. It is noticed that one of the means to make a system agile in dealing with changes is to break a 'permanent' relationship between system components. However, such non-permanent relationships may cause some problems in the reliability which may have negative impacts on the performance of a whole system. The research objective is toward a better understanding of types of such non-permanent relationships with respect to types of components in a particular social and business environment.

A project being carried out by authors, which implements the above ideas, has been briefly described.

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