



Knowledge management for consumer-focused product design

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As the automotive industry adopts a consumer focus in its product development strategy, it offers broader product ranges, shorter model lifetimes and the ability to process orders in arbitrary lot sizes. This offers the ability to conduct early product design and development trade-off analysis among these competing objectives. A distributed knowledge-based system, which analyzes, verifies, stores, and retrieves process definitions, is needed to manage the complexity of workflows. The use of information technologies and networking capabilities is essential in the dissemination of product knowledge in order to integrate the decision-making process among heterogeneous and distributed partners/units. This paper offers insights into a knowledge management approach that enables implementing a consumer-focused product design philosophy by integrating capabilities for intelligent information support and group decision-making utilizing a common enterprise network model and knowledge interface through shared ontologies. An automotive supply chain case study is utilized in illustrating the proposed approach.

Keywords: Supply chain data modeling, supply chain knowledge management, supply chain configuration management

1. Introduction

As manufacturers' increasingly adopt a consumer focus in their product development strategy, a new paradigm in product design and manufacturing is emerging. It offers broader product ranges, shorter model lifetimes and the ability to process orders in arbitrary lot sizes. Central to this strategy is the ability to conduct early product design and development trade-off analysis among these competing objectives. This requires coordination of related business/engineering processes (workflows) in the delivery of the product through geographically and institutionally distributed capabilities. A distributed knowledge management environment comprising, (a) a knowledge-based system, which analyzes, verifies, stores, and retrieves process definitions, and (b) a process manager, which manages and monitors execution of processes defined in the knowledge base system is

needed to manage the complexity of workflows. The use of information technologies and networking capabilities is essential in the dissemination of product knowledge in order to integrate the decision-making process among heterogeneous and distributed partners/units.

This paper offers insights into a knowledge management approach that enables implementing a consumer-focused product design philosophy by integrating capabilities for intelligent information support and group decision-making utilizing a common enterprise network model and knowledge interface through shared ontologies. First, concepts, trends and impact of consumer-focused product design on manufacturing operations in a complex business enterprise system, such as a supply chain are described. Then, we discuss major requirements and interconnections for knowledge management in consumer-focused product design. Based on these

requirements, we describe a framework of knowledge management through shared ontologies for consumer-focused product design, laying out the blueprint of integrating information support for decision-making activities in an enterprise. It is based on modeling an enterprise as a dynamic constraints network and has three main components, namely a methodology, techniques, and tools. An automotive supply chain example brings together various concepts in the proposed framework. Finally conclusions and directions for future research in this topic are highlighted.

2. Consumer-focused product design: Concepts, trends and impact

As manufacturers explore newer markets, they are increasingly targeting products to meet consumer needs and preferences. Further, products are being designed to offer both tangible and intangible benefits commensurate with these needs and preferences. This requires ensuring a balance between anticipated product features and benefits. A consumer-focused product design strives to simultaneously meet some of the conflicting objectives of consumer and manufacturer/seller. It is based on premises that (a) changing customer requirements dictate varied product features, (b) structure of products and processes must be aligned with dynamic product features, and (c) manufacturing productivity requires managing conflicting objectives due to these structural alignments. We discuss each of these below.

The first premise ensures that product features are designed to offer—style and technology to satisfy technical feasibility; utility, value, and price to meet economic feasibility; and quality, and reliability to meet operational feasibility of product design.

The second premise mandates clustering products based on common product features (attributes) and then mapping to identical processes and/or operations. This strategy results in reduced lead-time, set up time, resource utilization, process flow, and costs.

The third premise requires managing effects of first two premises on manufacturing productivity in the presence of multi objectives caused by product-process realignment. That is, the impact of product variety management on time-to-market (lead-time, set up time), cost, and scaling of manufacturing/production operations (lot sizing). There are many trends, especially related to concepts described above that are

relevant to consumer-focused product design. These relate to product-process orientation, enterprise configuration/reconfiguration, and the use of information technologies in decision-making. We describe some of the prominent ones below.

2.1. Mass customization and product postponement

Mass customization operates with product configuration, in order to adapt to customer requirements through mass production of individually customized goods and services. Da Silveria *et al.* (2001) in their recent review paper summarize several factors that enable a successful implementation of mass customization strategy. A balance between customer expectations about price and delivery promptness of customized products and producers' ability to schedule within an acceptable cost and time frame is put forward as one of the conditions required for successful implementation of mass customization. They also state that an efficient production network should be available for implementation of this strategy. If other conditions are met, then finding the balance and a production network configuration supporting it remains an ultimate decision making goal. The balance can be characterized by delivery time and inventory held to secure the service level. In such a setting, the problem of adopting mass customization policies directly ties with postponement. Customization is achieved by postponing some production activities until customer orders are received. Production is finalized according to ordered product specification. In a multi-stage production system, there would be a stage, starting from which production is initialized only upon receiving customer's order. Postponement may entail re-designing products using modularity and commonality as design principles (Van Hoek, 2001). Also influenced are product and process design so as to differentiate between discrete, continuous, and decoupled processes.

2.2. Supply chain

The implementation of mass customization and postponement strategies also affects the structure of the enterprise because postponement activities will most likely be placed close to the market, which reflects demand emanating from consumers. As

products are designed in accordance with these strategies, it is imperative their effects be implicitly reflected in the design of supply chain from sourcing to final distribution of products. Supply chain is a special form of complex business enterprise system, where the key is to co-ordinate information and material flows, plant operations, and logistics (Lee and Billington, 1993). The fundamental premise of a supply chain management approach is synchronization among multiple autonomous business entities represented by it. That is, improved co-ordination within and between various supply chain members. Co-ordination is achieved within the framework of commitments made by Members to each other. Increased co-ordination can lead to reduction in lead times and costs, alignment of interdependent decision-making processes, and improvement in the overall performance of each member, as well as the supply chain network (group) (Chandra, 1997; Sousa *et al.*, 1999). The most common form of supply chain decision-making is aimed at managing business-to-business, and business-to-consumer model for service and goods transactions.

2.3. Information technologies

Information technologies designed and implemented for business-to-business, and business-to-consumer models impact the market substantially by driving costs down through standardized networking technologies, and creation of entirely new enterprise and/or relationships by real-time interconnection of companies with their customers. These technologies have a strategic objective of managing customers' needs by way of a proactive "consumer pull", as against the traditional "product push" strategy. A heavy emphasis is placed on customer relationship management, which involves identifying goals (customers wants and needs), and developing marketing programs aimed directly at fulfilling these goals.

Implementation of above information technology strategies requires capabilities for real-time decision support. The challenge is to accommodate interaction of various units with competing objectives as they share information with each other toward achieving their shared goals. Therefore, e-management has come to symbolize a management philosophy that reflects important traits of the global digital economy, namely dynamic real-time decision-making, customer orientation, and speed in responding to market

demands. This topic has evinced interest on various aspects of the problem based on Internet technologies, such as e-commerce, e-business, and e-manufacturing.

2.4. Impact of consumer-focused product design on manufacturing operations

An intelligent enterprise, such as a supply chain utilizing e-management capabilities may be emancipated in the form of a virtual enterprise to support manufacturing operations. The major component of this enterprise form is intelligent information support utilizing state-of-the-art in information technologies. Decision-making capabilities in this enterprise form are "on-line", thus offering a dynamic environment. Some of the labels given to operations of this enterprise are, virtual manufacturing, and/or e-manufacturing.

Virtual enterprise is a temporal co-operation of independent units (enterprises, institutions, or individuals), which provide a service on the basis of shared skills, technologies and resources. Figure 1, depicts a virtual enterprise template. Its components are a set of technology and associated resources (A, B, C, etc.) available to a unit(s) i , belonging to a virtual enterprise at time intervals (T_j, T_m) . Units of a virtual enterprise may share common technology and associated resources through coalition agreement(s). Sharing is facilitated through logistic systems, connected via common objectives and policies for implementation.

One of the phases of virtual enterprise creation is its configuration, necessitated by market conditions that dictate uniquely structuring its product, process, and resource components. As depicted in Fig. 2, the interaction among these components brings complexity to enterprise structures. Thus, the need for knowledge management in an enterprise, and an integrated knowledge base system to support it.

To support this need, it is imperative that knowledge about an enterprise be designed with the view of integrating its product, process, and resource components.

One of the emerging forms of a virtual enterprise is a supply chain, the basis of knowledge management framework described in the rest of the paper.

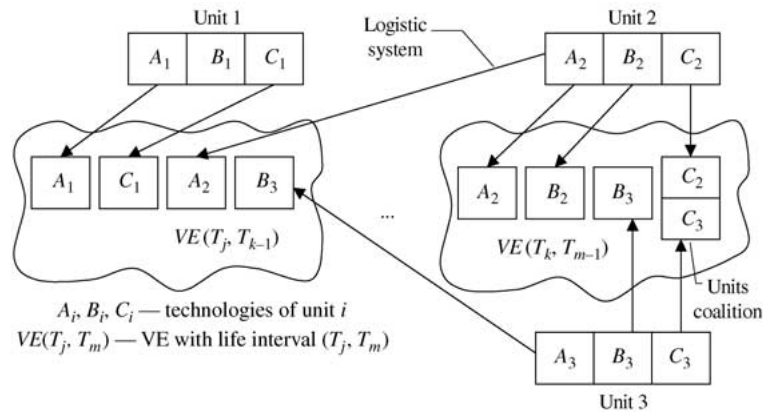


Fig. 1. A virtual enterprise conceptual template.

3. Knowledge management for consumer-focused product design: Requirements and interconnections

An e-management strategy adopted by the supply chain is focused on value creation. The focus of this strategy is to increase supply chain efficiency and reduce overall costs. These are primarily achieved through supply chain integration.

For efficient management of supply chain, it is essential that its design be properly configured. An important facet of configuration is to understand the relationship between supply chain system components that define its structure, namely products, processes, and resources. The primary goal is to facilitate transfer and sharing of knowledge in the context of new forms of supply chain configurations, developed in response to changing consumer focus in product design.

Figure 3 depicts a template used in describing interconnectedness between problem solving approaches and technologies for the enterprise information environment. The proposed approaches and associated technologies are categorized into two groups, (i) problem solving, and (ii) information support. For the first group, these are (1) custom-ordered (mass customization) management (2) configuration management, and (3) constraint satisfaction and propagation. For the second group, these are (a) data and knowledge management, (b) ontological representation of knowledge, (c) multi-agent and intelligent agent, and (d) conceptual and information modeling. For the purpose of the framework described in this paper, we focus our attention on items (a) and (b) of the second group with their interconnections to remaining items of both groups, respectively.

We describe below various approaches and technologies identified in Fig. 3.

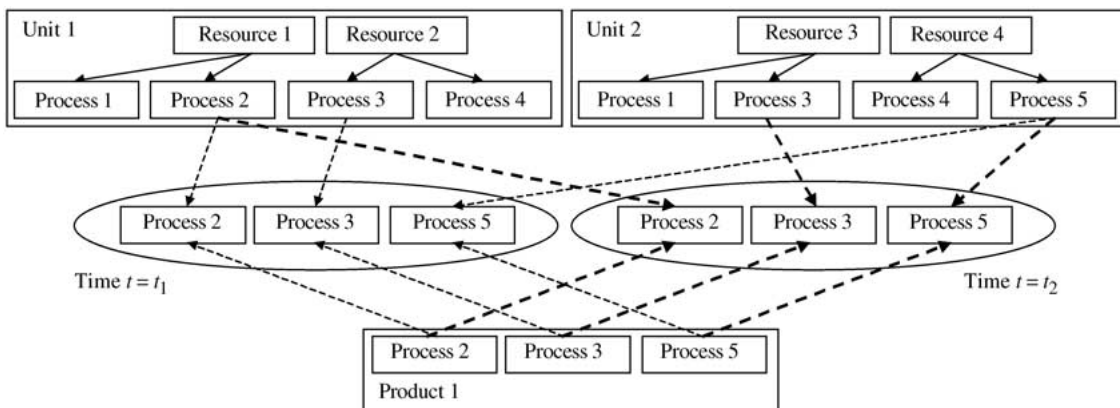


Fig. 2. Cascade scheme of virtual enterprise structure.

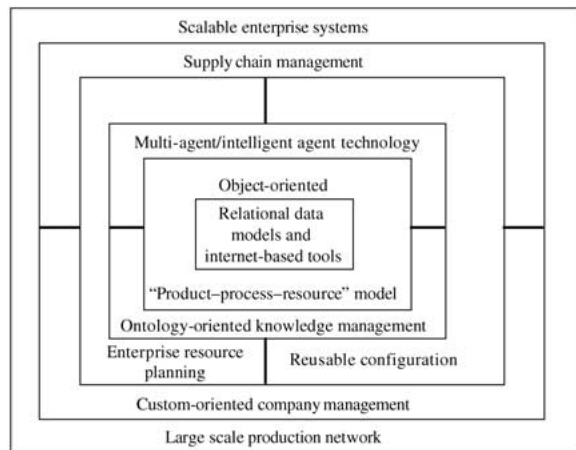


Fig. 3. Interconnectedness of problem-solving approaches and technologies.

3.1. Configuration management

The objective of designing an intelligent enterprise utilizing configuration principles is to generate customized solutions based on standard components, such as templates, baselines, and models. There are two aspects to configuration management: (i) configuring/reconfiguring and (ii) configuration maintenance. Configuring deals with creating configuration solutions and selecting components and ways to configure these. Configuration maintenance deals with maintaining a consistent configuration under a dynamic environment. This requires consistency among selected components and decisions. Accordingly, when a decision for selected component changes, configuration maintenance must trace all related decisions and revise them, if necessary.

3.2. Constraint satisfaction and propagation

Constraint satisfaction is a fundamental problem for management and engineering activities. Traditional constraint satisfaction procedures have been designed for the problem with a fixed set of constraints. In the design of a supply chain, it is often necessary to solve a dynamic constraint satisfaction problem, where applicable constraints depend upon various design aspects and time horizons.

3.3. Multi-agent and intelligent agent

Implementation of the basic principle of cooperation in the supply chain is based on distribution of

procedures between different units/users (or agents) concurrently in the common knowledge space. It is, therefore, natural to represent configuration management knowledge as a set of interacting autonomous agents in a multi agent environment. Agent is a mechanism that facilitates capturing behavioral characteristics of the problem for a specific process or activity. Intelligent agent is an entity that can navigate in heterogeneous decision-making environment, and either alone or working with other agents, achieve specific goal(s).

3.4. Conceptual and Information modeling

In order to design and implement a supply chain, it is important to explore and understand its structure and behavior as a system under dynamic environment. Conceptual and information modeling enables representation and evaluation of system entity characteristics, relationships to other entities, and controls to achieve objectives. Some of the techniques utilized for evaluation of various enterprise configurations using enterprise-wide database are: process modeling, entity relationship modeling, object-oriented modeling, and genetic algorithms.

In order to coordinate flow of materials within a multi-echelon supply chain, it is important to synchronize activities both at inter and intra levels by sharing information. For this purpose, it is imperative that activities between trading partners are based on a set of commercial and contractual rules that identify protocols necessary to guarantee cooperation and coordination. To support this objective, an information kernel in the form of a ‘‘supply chain conceptual model’’ is needed. This kernel describes major components of a supply chain as a set of: objectives at strategic level, namely supply chain model attributes, strategies, supply chain units, constraints for every unit, products for every unit, unit resources, contract relationships among units, and coefficients for bilateral relationships among units.

3.5. Data and knowledge management

Data and knowledge management offers intelligent support, critical to realizing competitive advantage for a supply chain. System information integration deals

with achieving common interface “within” and “between” various components at different levels of hierarchies, different architectures and methodologies (Hirsch, 1995; Sousa *et al.*, 1999) using distributed artificial intelligence and intelligent agents (Fischer *et al.*, 1996; Gasser, 1991; Jennings *et al.*, 1996; Jennings, 1994; Lesser, 1999; Sandholm, 1998; Smirnov, 1999; Wooldridge and Jennings, 1995). Knowledge modeling and ontologies describe unique system descriptions that are relevant to specific application domains (Fikes and Farquhar, 1999; Gruber, 1995; Gruninger, 1997; Smirnov and Chandra, 2000).

Knowledge is a set of relations (constraints, functions, and rules) by which a user (agent) decides to use the information in order to perform timely actions in meeting a goal or a set of goals. Knowledge sources include:

- database and knowledge base,
- documents stored in Internet/Intranet/Extranet,
- expert knowledge,
- libraries of solved problem case description,
- libraries of standard situation description.

Knowledge is the key to managing collaborative activities in the supply chain. Therefore, knowledge must be relevant to overall business goals and processes and be accessible in the right form when needed. An important requirement for an integrated knowledge base system is the ability to capture knowledge from multiple domains and store it in a form that facilitates reuse and sharing. This is accomplished via design and development of knowledge management mechanisms with following knowledge levels:

- System knowledge describing rules for integration between units (manufacturer and its extended supplier and dealer network) of the enterprise, and its management and maintenance.
- Facilitator knowledge describing rules for distribution of knowledge and identification of access level in sharing data and knowledge base.
- Unit knowledge describing reusable methods, techniques and solutions for problem solving at the unit level.
- User knowledge describing knowledge related to individualized special skills of a user at the problem domain level.

3.6. Ontology

Ontology is a form of knowledge representation applied in various domains. A FIPA definition of ontology is as follows (FIPA 1998):

- Ontology is an explicit specification of the structure of a certain domain.
- Ontology includes a vocabulary (i.e., a list of logical constants and predicate symbols) for referring to the subject area, and a set of logical statements expressing constraints existing in the domain and restricting the interpretation of the vocabulary.
- Ontology provides a vocabulary for representing and communicating knowledge about some topic and a set of relationships and properties that hold for entities denoted by that vocabulary.

Ontology is useful in creating unique models of a supply chain by developing knowledge bases specific to various problem domains. Ontologies are managed by translation and mapping between different types of entities and attributes. These capture rules and constraints for the domain of interest, allowing useful inferences to be drawn for execution, analysis, and validation of models. Ontological translation of an enterprise, such as a supply chain is necessary because networks are multi-ontology classes of entities. Various ontologies for an entity describe its unique characteristics in context with the relationship acquired for a specific purpose or problem. Each user (agent) works with its own ontology-based knowledge domain model (Fikes and Farquhar, 1999; Jennings, 2000; Fox and Gruninger, 1999; Uschold and Gruninger, 1996; Rubenstein-Montano *et al.*, 2001; Vasconcelos *et al.*, 2000).

4. Ontology-driven knowledge integration as a knowledge management technology framework for consumer-focused product design

The complexity of problem-solving requirements described in the previous section, point to the need of offering decision-making capabilities that integrate knowledge development methodologies, techniques, and tools seamlessly. We describe a framework of knowledge management for consumer-focused product design that lays out the blueprint of integrating information support for decision-making activities in

an enterprise. It is based on modeling an enterprise as a dynamic constraints network and has three main components:

- (1) a methodology for supporting knowledge management needs of a dynamic constraints network,
- (2) techniques for design and modeling of knowledge base system based on taxonomical descriptions of the problem-solving environment in a complex enterprise system,
- (3) tools for design, modeling, implementation and evaluation of the problem-solving environment in a complex enterprise system.

We describe each of these below in the context of a supply chain.

4.1. Methodology

In order to design a supply chain that can be configured to meet changing production needs, relationship between system structures due to “product–process–resource”, interactions must be understood. In such an environment, the supply chain is able to trade product models on a business network that make realization of an integrated virtual supply chain possible. Also, supply chain configuration generates customized solutions based on standard components (as templates or baselines), or supply chain model. Hence, the implementation of supply chain approach is based on the shareable information environment that supports the “product–process–resource” model of an enterprise. A generic enterprise model may be defined as follows:

- Natural language explanation of the meaning of modeling concepts—glossaries of terms.
- Some forms of meta models, e.g., process models, entity relationship, meta schema, and conceptual models of terminology component of modeling languages, describing relationships among modeling concepts.
- Ontological theories defining the meaning (*semantics*) of enterprise modeling concepts, in order to improve the analytic capability of decision-making, and through these the usefulness of enterprise models.

An important requirement for a collaborative system is the ability to capture knowledge from multiple domains and store it in a form that facilitates reuse and sharing (Sousa *et al.*, 1999). The metho-

dology suggested in this paper is limited to designing knowledge management capabilities for product–process–resource configurations, focused on utilizing reusable knowledge through ontological descriptions of a dynamic constraints network. This is accomplished by knowledge modeling product, process, and resource components to satisfy manufacturing constraints in a firm’s environment. Reusable knowledge management deals with organizing “knowledge clusters” by their inherently common characteristics, as observed in various problem domains; and utilizing these as templates to describe unique conceptual models of an enterprise or its components. It is based on GERAM, the Generalized Enterprise Reference Architecture and Methodology (ISO TC 184/SC 5/WG 1, 1997) at the domain level; and MES (MESA, 1998), MEIP (MEIP, 1999), NIIIP (NIIIP, 1994) and WFM (WFM, 1996) methodologies at the application level.

A dynamic constraints network provides the basic structure for supply chain configuration in the above methodology. Constraint satisfaction is a fundamental problem for solving supply chain issues. Conventional constraint satisfaction procedures are designed for the problem with one constant set of constraints. However, in manufacturing systems (design for productivity, configuration, layout, and scheduling), it is often necessary to solve a dynamic constraint satisfaction problem where applicable constraints depend on design aspects (Smirnov, 1994). The domain knowledge model of supply chain contains entities (objects), which can be of different types (classes). Multi-level representations are used for product–process–resource model description. In addition, each unit (supply chain member) may work with its own ontology-oriented constraint network. Thus, the dynamic constraints network approach presented in this paper with interconnectivity between design and production features reflecting complete association of product, process, and resource components in the supply chain offers the capability to model integrated solutions to problems.

An abstract product–process–resource model is based on the concept of ontology-oriented constraint networks. Multi-ontology classes of entities, attribute logic and the constraint satisfaction problem model represent networks. This abstract model unifies main concepts of languages, such as standard object-oriented languages with classes, and constraint programming languages. It supports the declarative

representation, efficiency of dynamic constraint solving, as well as problem modeling capability, maintainability, reusability, and extensibility of the object-oriented technology (Smirnov and Chandra, 2000).

The ontology-oriented constraints network model is denoted, $A = (St, C)$, where St , is an ontology structure, C , is a set of ontology constraints. To deal with the conceptual schema of configuring process defined in terms of constraints, a dynamic constraints network model is applied. A static constraints network $A_i = (V_i, D_i, C_i)$, involves a set of variables $V_i = (v_{i1}, v_{i2}, \dots, v_{iN_i})$, each taking value in its respective domain $D_i = D_{i1} \times D_{i2} \times \dots \times D_{ij} \times \dots \times D_{iN_i} = \prod_{j=1}^{N_i} D_{ij}$, and a set of constraints $C_i = \{c_{i1}, c_{i2}, \dots, c_{ik}\}$. A dynamic constraint network N is a sequence of static constraints networks, each resulting from a change in preceding one imposed by the external environment.

For design of supply chain knowledge base, we utilize ontology design. It is based on an ontology hierarchy, depicted in Fig. 4. The top-level ontology is the “shared ontology” for domain independent representation of the problem set. This type of ontology is needed to describe an abstract model using common knowledge representation. The lower-level ontology is “application ontology” and is a combination of the “domain specific ontology” and the “problem-specific ontology”. This type of ontology is needed to describe special knowledge about an application or a problem for unit and user. The top-level ontology is oriented for dynamic constraints network, while the lower-level ontology is for ontology-based constraints network. The product configuration is represented by the following

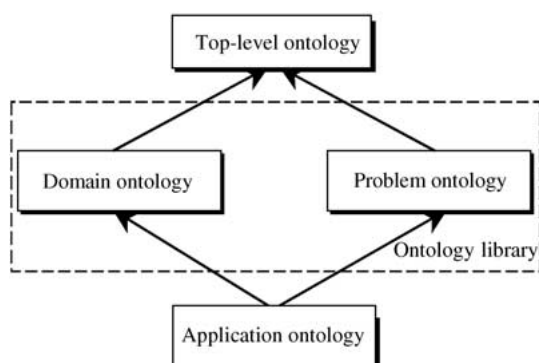


Fig. 4. An ontology management hierarchy for knowledge base system.

relationship: “configuration of the product (product structure, materials bill) → configuration of the business process (process structure, operation types) → configuration of the resource (structure of system, equipment and skill levels)”.

Applying above methodology enables forming the conceptual model of the supply chain system. This is accomplished by knowledge modeling its product, process, and resource components to satisfy manufacturing constraints in its environment. The implementation of this approach is based on the shared information environment that supports the product–process–resource model used for integration and co-ordination of user’s (unit’s) activity. This model is studied from various viewpoints of user (unit) groups as depicted in Fig. 5. It identifies relationships between various model types of the dynamic constraints network, their relationships to user types (agents) and respective data and knowledge needs.

An ontology management agent performs the function of employing the product–process–resource model at various levels of decision-making to provide solutions for problems at varying levels of complexity. For instance, in Fig. 5, models for product–customer or product–supplier are modeled at higher levels of abstractions since decision-making is at strategic level for complex top-level business problems. However, product–process–resource model for logistic manager are modeled at detailed levels for low-level routing, invoicing, and packaging problems.

Accordingly, the system is supported by a number of ontologies which are deployed as the decision-making process is invoked at various levels:

- Domain ontologies are designed to provide common high-level knowledge related to system structures and controls. The product, process, and resource system knowledge, their interactions in formulating various supply chain structures and controls that set boundaries of these relationships are examples of this type of ontology. It is usually designed for industry specific supply chain, or important function modules thereof.
- Service ontologies are designed to provide low-level knowledge needed to perform service functions for a larger strategic problem by solving lower level problems that improve operational productivity in a supply chain. For

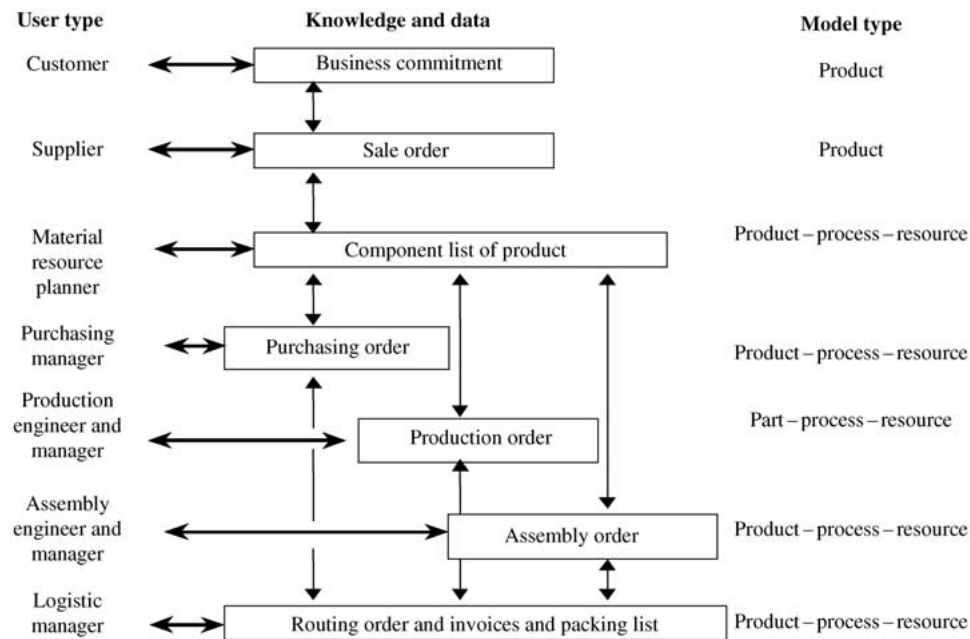


Fig. 5. Links of users to knowledge and data in supply chain.

example, for a strategic production planning and control problem in a supply chain, service ontologies will offer knowledge for specific solutions to demand forecasting, inventory management, capacity and production planning for multi-echelon planning systems.

- Ontology of administration and management are designed to provide knowledge to facilitate implementation of technical tasks, such as communication amongst various supply chain users (agents) utilizing appropriate protocols. It identifies administrative details such as, the unique address, as well as the networking protocol to be used when interfacing with the software system.
- Ontology of roles denotes roles and terms of engagement for transactions that agents may wish to play, namely supplier, consumer, producer, negotiator, and bidder as they negotiate services in the supply chain.

The above ontology management approach is based on two mechanisms (Smirnov and Chandra, 2000): (1) object class inheritance mechanism supported by inheritance of class ontologies (attributes inheritance) and by inheritance of constraints on class attribute values, and (2) constraint inheritance mechanism for inter-ontology conversion supported by constraint

inheritance for general model (constraints strengthening for “top-down” or “begin-end” processes).

4.2. Techniques and tools

For implementation of the methodology described in Section 4.1, a conceptual framework for supply chain information systems support architecture depicted in Fig. 6, is proposed using system taxonomy, process models, and ontologies. First, we offer below an overview of the framework, followed by description of its various elements.

General system taxonomy presents system components at highly generalized level. This presentation can be applied to any type of system. Supply chain inherits its features, thus offering system view of supply chain components and activities. Process model constructions are concerned with supply chain problem solving, modeling, analysis and implementation on the basis of supply chain problems taxonomy. The general purpose is to ascertain how characteristics of the product, process, and resource elements of the supply chain depend on the specific problem environment and to elaborate various supply chain process models. According to system approach applied to ontology development, ontological

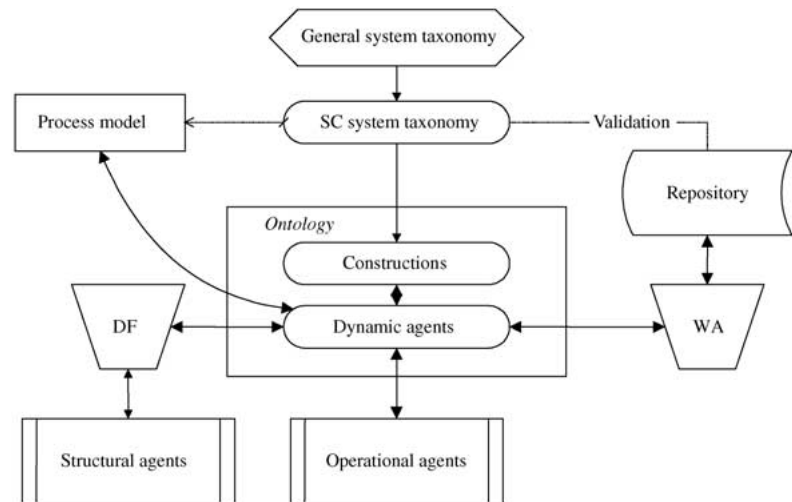


Fig. 6. Supply chain information system support conceptual framework.

constructions must be based on system taxonomy. Supply chain system taxonomy is a class structure, where supply chain characteristics are presented comprehensively. Ontological constructions are created from taxonomy, copying relationships between its characteristics and groupings. Every ontology is a subunit of taxonomy. Besides ontology structures must be validated by taxonomy, providing overseeing framework to ensure that general requirements are addressed.

Ontology server is a combination of ontological construction and dynamic agent modules. Dynamic agents are not real agents. They are mechanisms for creating ontologies as knowledge modules from ontological construction, which are actually knowledge representation formats only. Dynamic agents populate ontological constructions with data taken from central repository, such as an enterprise resource planning system database and send these to operational agents, which are problem-solving modules. Ontologies are also utilized by Structural agents, which are supply chain members, or groups of members. Dynamic agents also provide connection between process model structures and ontology, thus updating knowledge acquired from process models to central repository, or to operational agents.

Ontology is a structured and explicit object-oriented tree representation of characteristics about a particular problem-solving environment, or information about a specific domain. Ontologies are distinguished by two distinct ontology-types:

- domain ontology,
- problem solving or service ontology.

Ontologies may be represented as a scheme in XML files, which are supported by a majority of platforms and software development tools. The purpose for building ontology server is to enable technology that will provide large-scale reuse of ontologies, not only inside the enterprise, but also at a distributed level. Before building the server, ontologies must be built. Building ontology for a particular domain requires analysis, revealing relevant concepts, attribute relations, and constraint of the domain. This knowledge is acquired from taxonomy.

4.3. General system taxonomy

General system taxonomy seeks to incorporate process, environmental and other variables in a system. The resulting system would be based on variables that are measurable and tractable (Bertalanffy, 1975; Lambert and Cooper, 2000; McCarthy, 1995; McCarthy and Ridgway, 2000; McKelvey, 1982). The complexity and dynamic nature of contemporary manufacturing organizations complicate understanding about them. Separating system components with underlying variables into modules helps to map the system for further modeling and analysis. The proposed system hierarchy separates system taxonomy into three levels: system, enterprise system, and supply chain system. For each

level, a class diagram is proposed according to object-oriented modeling techniques.

Object-oriented approach attempts to create a hierarchy of classes. The most general class includes parameters and procedures that are relevant to any system. It can be an industry such as automotive, textile, or a small manufacturing line. The top class in our structure is system in general. System scientists describe general system with seven aspects, depicted in Fig. 7, part of a super system. The hierarchical structure is based upon the need for more inclusive clustering or combination of subsystems into a broader system, in order to coordinate activities and processes.

4.4. Supply chain system taxonomy

The system taxonomy is developed through systematic analysis of supply chain and enterprise characteristics. These characteristics illustrate supply chain and enterprise activities and processes. Generalizing from variety and complexity of parameters describing supply chain, essential parameters are chosen. Characteristics of a supply chain are not only distinguished by physical connections (number of products, types of participants, etc.), but also by operations, objectives and attributes such as manufacturing processes, business objectives and inventory needs. Before proceeding to data analysis, first a set of

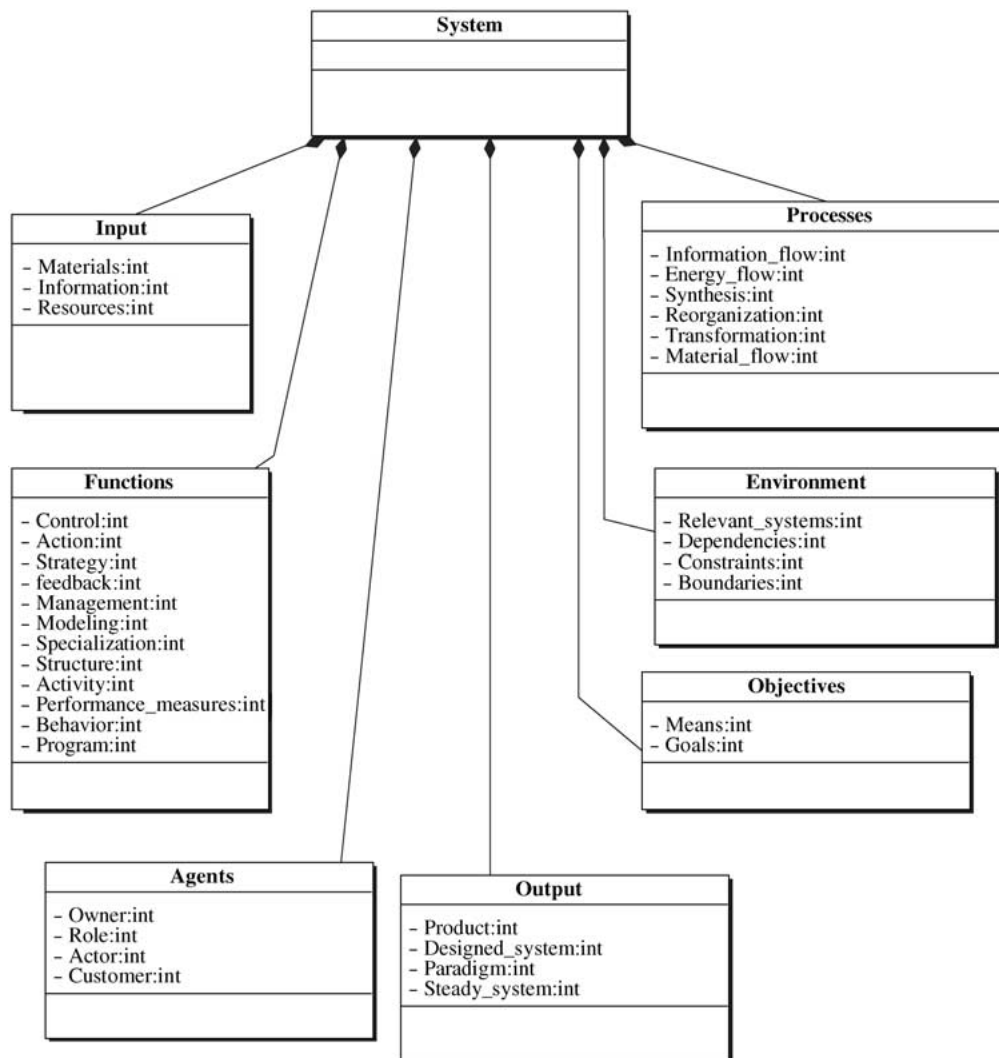


Fig. 7. General system taxonomy.

variables are defined and labeled operational taxonomic units, corresponding to general system components. The approach employed, first, reduces the concentration of data (data structure normalizing), accomplished by packing data in smaller groups of variables. Then, the configuration approach is used to identify classification or taxonomy of overall system. Supply chain, assumed as being a specialization of general system, inherits its structure and parameters. The final structure depicted in Fig. 8, represents

general and special components distributed in seven subunits, and taken from general system taxonomy: input, output, objectives, processes, functions, environment, and agents. In these subunits, characteristics are represented by small groups of attributes. What differentiates supply chain from general system is its specialization level. Therefore, all components are more specific, and relevant to a supply chain domain.

The organization of proposed taxonomy was designed to accommodate supply chain and enterprise

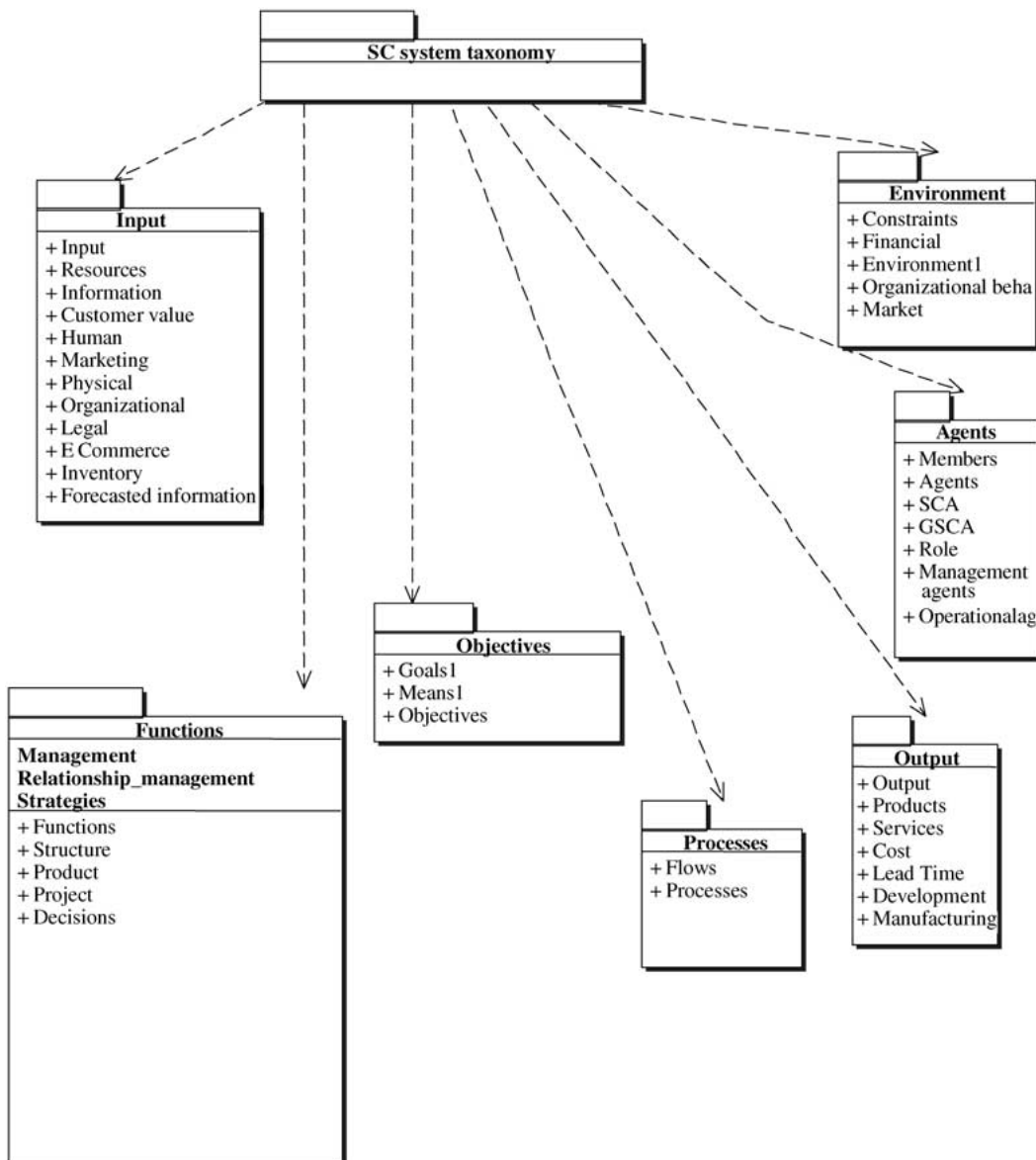


Fig. 8. Supply chain system taxonomy.

characteristics, which will help to solve supply chain management problems, thus providing information support system with systematic mechanisms for dealing with complex data. The supply chain system taxonomy proposed in this paper has aided in the development of system representation of supply chain, with whole part relationships. It utilizes an object-oriented representation, focused on effective modeling of information system dealing with tasks of supply/production/distribution.

Utilizing these characteristics, we can start building information meta-model by:

- starting with system taxonomy structure;
- finding classes, where above mentioned characteristics exist and selecting these for the problem;
- deleting all other classes and packages.

As a result, an information presentation format is developed, which can be used by the model. There are two main reasons for utilizing these steps, instead of using the plain list of characteristics. First, these steps offer a standardized format needed by computational tools, which is common for every problem-solving environment. Second, these steps allow reusability of the same structure, whereby any other module can use results from this problem-solving module. Information structure meta-model for inventory control utilizing this technique is depicted in Fig. 9.

4.5. Product-process-resource model taxonomy

The supply chain configuration is presented by following relationship: “configuring the product (product structure, materials bill) → configuring the business processes (process structure, operation types) → configuring the resource (structure of system, equipment and staff types)”. An abstract product-process-resource model is based on the concepts of ontology-oriented constraint networks. The dynamic constraints network is a model to solve constraint satisfaction problem represented by ontology of entities. Based on concepts of the dynamic constraints network, the taxonomy of product-process-resource model is elaborated in Fig. 10.

The taxonomy of product-process-resource model represents the tree of taxa, set of characteristics of supply chain, combined by their internal homology. Processes of supply chain are described in taxonomic

representation as flows and transformation synthesis, which are transformation of flows. Flows of supply chain are financial, information, material, and product. Depending on the selection of elements from product-process-resource model taxonomy, the supply chain process model construction will change.

4.6. Supply chain process model construction

The entity of supply chain process model can be considered as a system with corresponding parameters: input, output, function, rules, agents, processes, and environment. Only production unit entity fulfills requirements of system approach because it has all system parameters. Product entity is an element of supply chain that serves as an output of production unit entity. Entities of supply chain process model contain two types of attributes, which are properties and characteristics. Properties are attributes of entity describing input, output, function, and processes parameters of system and providing information about entity as a separate unit. Characteristics are attributes of entity describing rules, agents, and environment, and providing information about role of entity in the supply chain. Relationships between entities of supply chain process model must be met with some restrictions. For example, in this research two types of relationships have been implemented, namely those between product and production unit, and production units themselves (Curtis *et al.*, 1992; Johannesson and Perjons, 2001; Lambert and Cooper, 2000; Martin and Cheung, 2000; Landauer, 2000).

4.7. Ontology development

We advocate the use of ontology as a means of bridging domain analysis (taxonomy) and application system construction (or decision modeling system). Our approach is to consider ontologies as the basis for specifying models in a specific problem domain (forecasting management, inventory control, production scheduling, etc.). The scope of ontologies is restricted to a particular problem domain, which permits assumptions to be made with regard to system architecture related to the problem-solving environment. On this basis, concepts in the ontology can be explicitly linked to software component capabilities, enabling the ontologies to serve both as

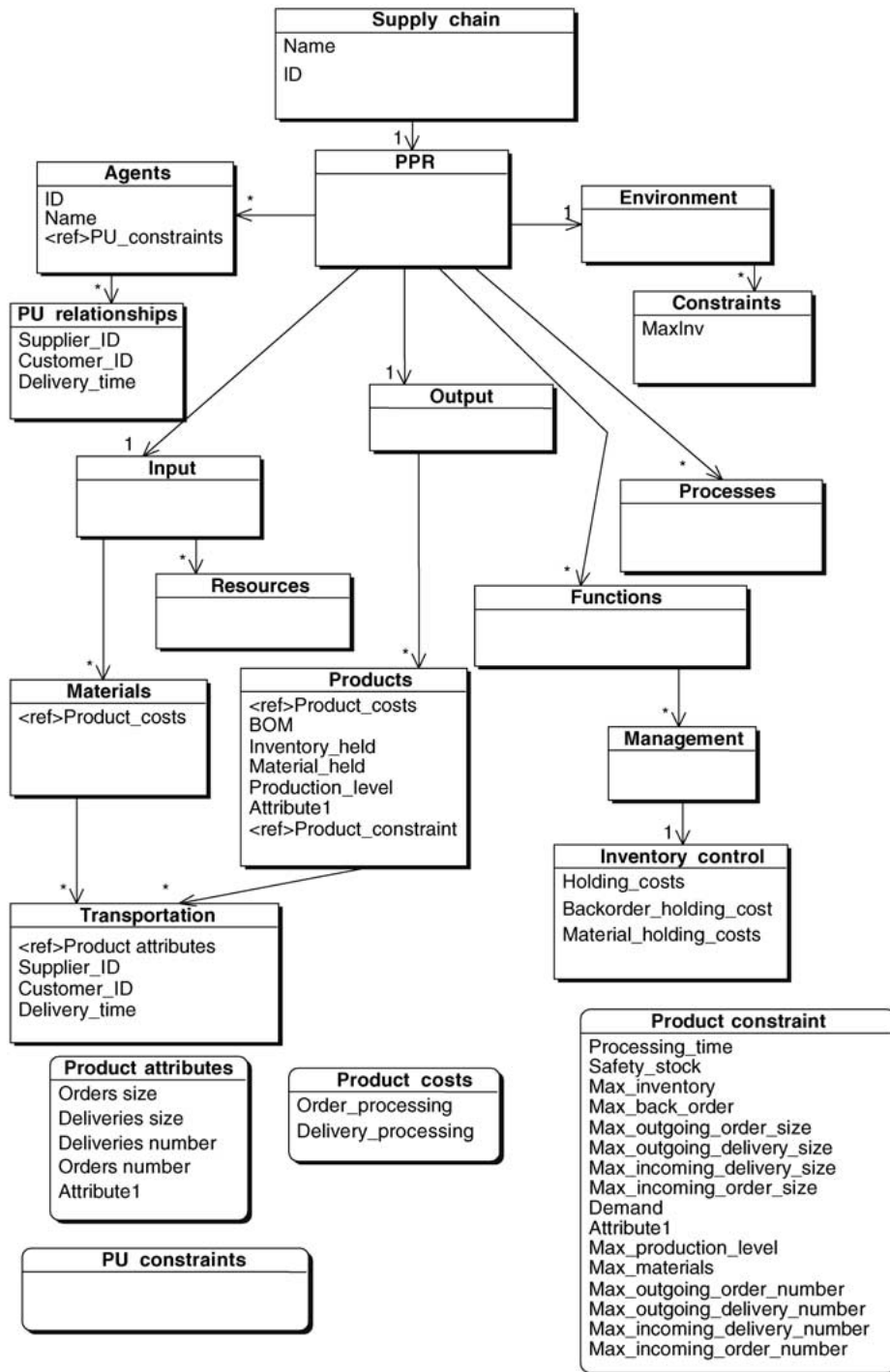


Fig. 9. Information model: Ontology.

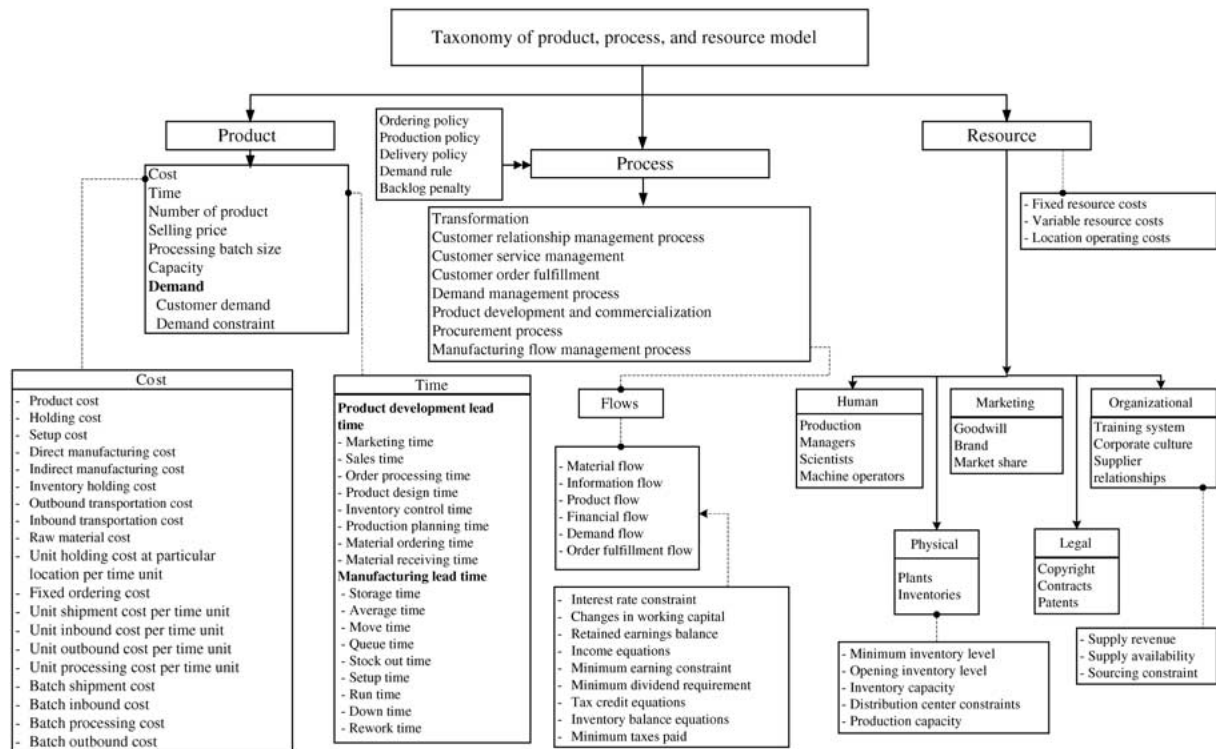


Fig. 10. Product–process–resource model taxonomy.

mechanism for indexing relevant software components and as specification of overall configuration requirements.

Considering inventory level optimization as a problem, we need to create its information model. But before building a model we have to collect characteristics, which describe the problem. The focus of our study is how to make those characteristics reusable and applicable for solving other problems that arise in the supply chain environment. The idea of creating ontology is to create a repository of characteristics grouped in object-oriented hierarchy. Ontology $A_i = (V_i, D_i, C_i)$ is a static constraints network, which contains three parts: variables V_i taken from particular domains D_i , and constraints C_i for these domains.

Utilizing these characteristics, we can start building information meta-model by:

- starting with system taxonomy structure;
- finding classes, where above mentioned characteristics exist and selecting them for the domain problem;

- building product-process-resource information model, utilizing UML/XML diagram with classes taken from taxonomy;
- giving initial values to characteristics.

As a result, an information presentation format is developed, which can be used by the decision model. There are two main reasons for utilizing these steps, instead of using the plain list of characteristics. First, these steps offer a standardized format needed by computational tools, which is common for every problem-solving environment. Second, these steps allow reusability of the same structure, whereby any other module can use results from this problem-solving module. Ontology information structure meta-model for Inventory Control is depicted in Fig. 9.

Supply chain management concept is an approach to industrial network enterprise creation and reuse that considers enterprises as assemblies of reusable units defined on shared “product–process–resources” domain knowledge model. Each object of above model represents knowledge about an agent charged with delivering a specialized technology. For

example, the supply chain agent is composed of one or more enterprise agents. Enterprise agent is composed of one each of inventory manager, capacity manager, and production manager agents. Similarly, inventory management agent is composed of one each of forecast management, inventory control, and raw material management agents. This relationship between agents signifies coordination of strategies, policies, goals, and objectives among them for problem-solving in specific domain.

Figure 11, depicts an object-oriented domain problem-solving/service ontology model for the inventory management agent. Its main components are inventory control, forecast management, and raw materials management agents, each of which carries specialized knowledge about these expertise areas/topics. For a supply chain, the object-oriented domain descriptions are as follows:

- Object supply chain describes the specific domain product supply chain agent.
- Object enterprise describes various member agents for this particular product supply chain,

i.e., retailer, assembler, component manufacturer, and end-product manufacturer, etc.

- Objects inventory, capacity, and production describe agents with specialized knowledge in these fields.
- Objects FM, IC, and RMM describe agents with domain knowledge in the areas of forecasting management, inventory control, and raw materials inventory management, specific to inventory management.

Each agent is characterized in terms of services. A description of services for forecast management agent is provided in Table 1 with corresponding ontology class. The service description is XML codified. Agents register their services with the domain facilitator (DF), depicted in Fig. 6. All offered services are invoked by sending a message to the corresponding agent. Implementation of the communication language permits defining multiple ontologies in the message parameter section.

In this service “forecast”, both service ontologies

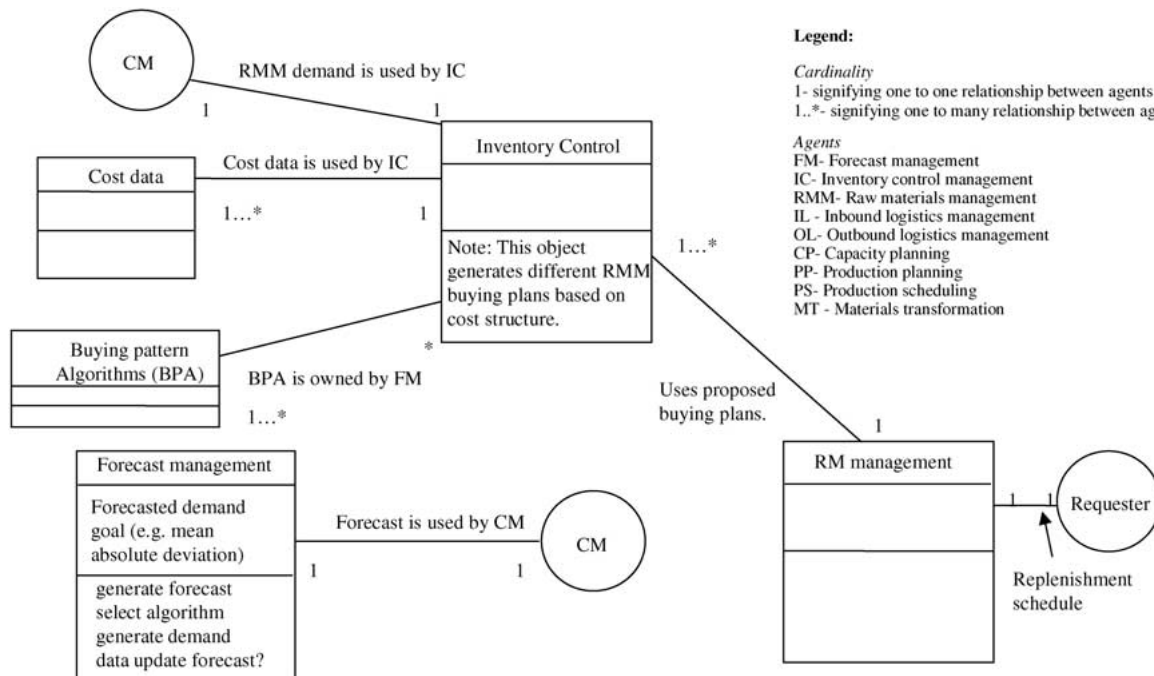


Fig. 11. Inventory management domain object problem-solving/service ontology model.

Table 1. Service “forecast” description for invoking ontologies

Agent: sub-agent Forecast:	
:service-name	generateForecast
:service-description	Utilizing demand data generate a forecast time series
:service-pre-defined constants	time (period) = 52
:service-type	Data manipulation
:service-ontology	ForecastManagement
:service-fixed-properties	forecast_error_max
:service-negotiable-properties	forecast_error_min, price
:service-communication-properties	FIPA-Iterated-CNP, FIPA-Auction

and ontology of administration and management are invoked.

5. Case study

An automotive supply chain example for mass customization of products is used for illustration of the knowledge management feature of the supply chain configuration management approach. This supply chain represents manufacturing of four main car components (body, interior, under carriage and

power train) and approximately 40 components, which enables us to model different production strategies, such as assemble-to-order, produce-to-order, and produce-to-stock, and different supply chain production system configurations described later in this section. A generic example of automotive supply chain is depicted in Fig. 12. In order to configure the automotive supply chain, it is represented as a dynamic constraint network (DCN), where each supply chain or its component is a sub-network, $SC = (P, Pr, R)$, where P is a set of SC members or production units for a set of products, Pr is a set of processes, and R is a SC resources available. The object model for this DCN presented in the following section represents above relations via a set of objects with appropriate properties (attributes), and events and methods (Dey *et al.*, 1999; Ettl *et al.*, 2000; Zhao *et al.*, 1999; Wand *et al.*, 1999).

5.1. Object-oriented model for supply chain

Utilizing these generic object-oriented structures, supply chain models as global enterprise models may be defined in various ways. Object-oriented models are formal models of concepts that are used in supply chain model representation. The highest level of object abstraction is object class, which depicts an

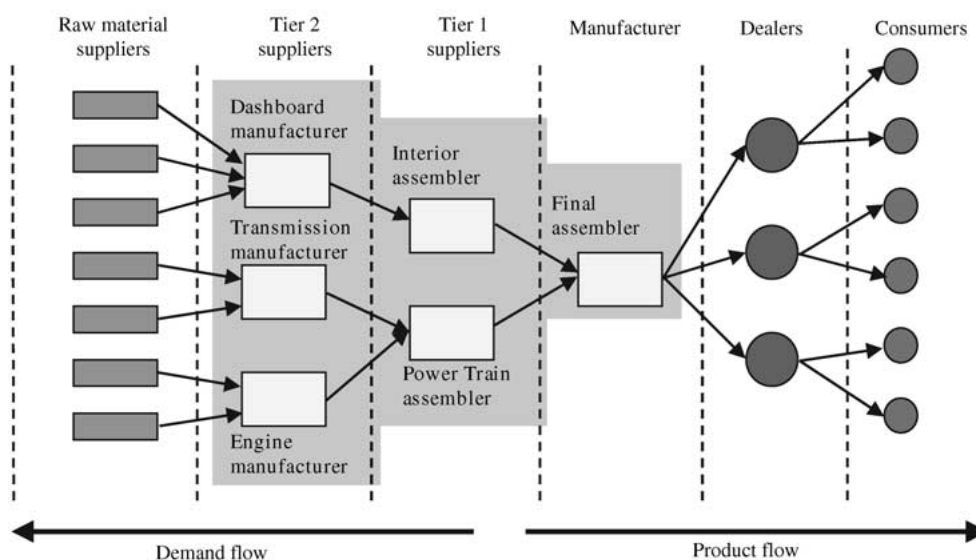


Fig. 12. A generic supply chain scheme (illustrating an automotive supply chain).

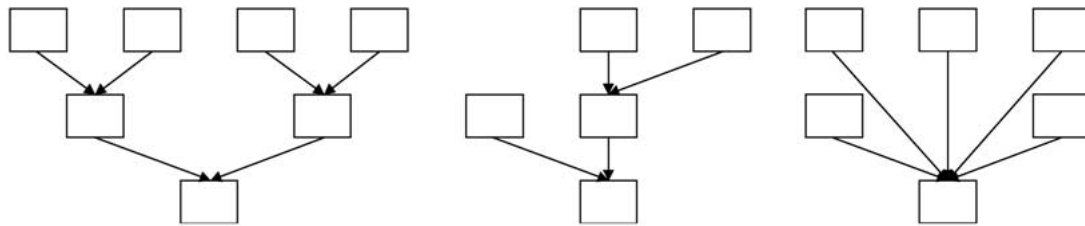


Fig. 13. Examples of parallel (left), sequential (middle), and distributed (right) supply chain configurations.

object's nature. The next level is object type, which belongs to one of the classes of the system and contains objects with similar properties. Every object has set of attributes, which shows the next attribute type level. Specific values for each object-attribute pair are stored at the next level of values. These relations may show structure of object and sequence of operations in a production process.

The object representation of supply chain must be able to handle supply chain features, such as divergent configurations that supply chain assume due to varied production strategies. For example, a supply chain may pursue production strategies that can adapt to one or more production system configuration, such as parallel, where some processes are performed in parallel (or concurrently); sequential or assembly,

where processes are performed one after another; satellite or distributed, where processes are performed at different locations that may be part of a manufacturing network as depicted in Fig. 13.

Database for these production models will have the same structure, but since each model has different tiers and particular supply chain configuration, it is represented by appropriate relations between all production units at different tiers. For example, in case of one-stage distributed production model, during the body assembly phase, assembly of all interior car components is performed and relations between all Tier-2 manufactures and body assembler are defined in the database. In case of parallel model, relations between production units of Tier-3, Tier-2 and Body Assembler are represented in the database.

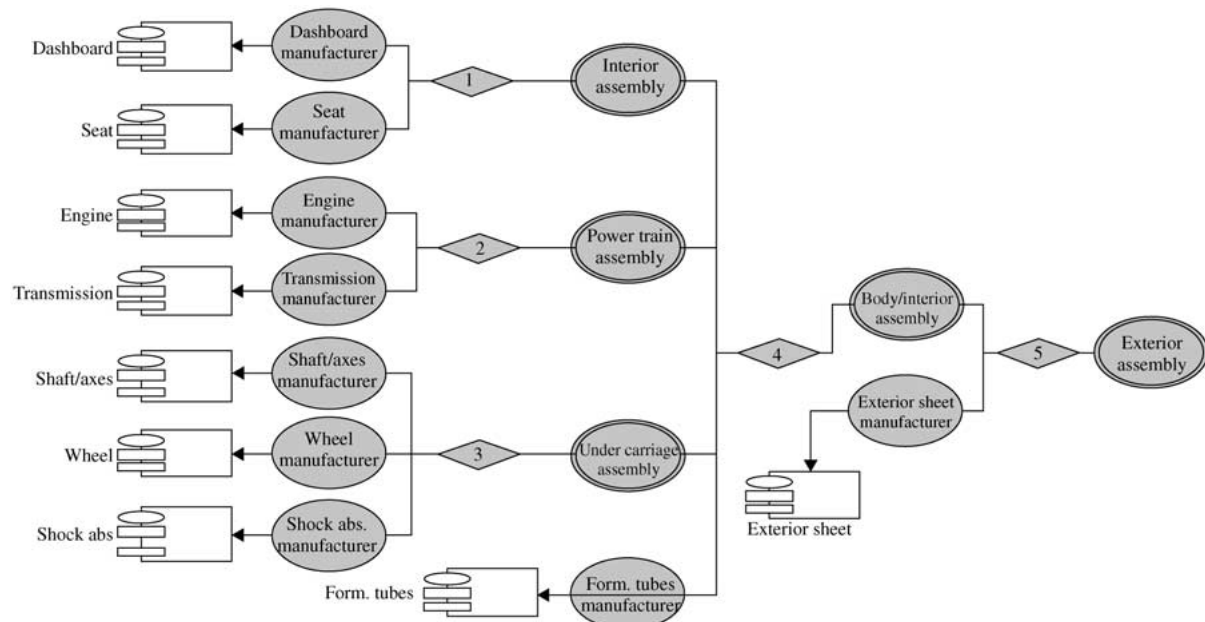


Fig. 14. Parallel distributed production model for an automotive supply chain developed in ARIS.

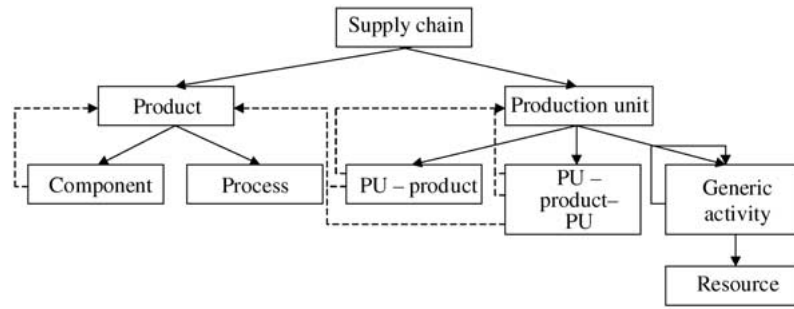


Fig. 15. An object representation of a generic supply chain structure as a dynamic constraints network.

To implement sequential distributed production model of supply chain, relations between four level components of Tier-4, Tier-3, Tier-2 and body assembler is determined. A process model representation was performed for the automotive supply chain utilizing a car with four main components body, interior, under carriage, power train, and several constructive elements within these components. In order to manufacture this car, various automotive supply chain production models may be created and different configurations evaluated using experimentation. For instance, a parallel distributed production model for an automotive supply chain developed using architecture of integrated information systems (ARIS) process-modeling software (Scheer, 2000) is depicted in Fig. 14. It has some processes, which are performed in parallel (or simultaneously). In general, process model construction is based on taxonomy of supply chain. However, construction of supply chain process model and selection of characteristics for objects of supply chain is based on taxonomy of product-process-resource model because it provides specific problem description. Ontology handler captures data from process model and passes them to central repository, which is SAP R/3 enterprise resource planning system database.

5.2. Object representation of a generic supply chain structure as a dynamic constraints network

The object representation of a generic supply chain structure as a dynamic constraints network is depicted in Fig. 15. The topmost object is a supply chain, the parent object for all objects in the dynamic constraints network. The objects at the next level are modified SC_DCN components, namely supply chain members or SC_ProductionUnit, and SC_Product with a one-to-many relationship. For example, the automotive supply chain depicted in Fig. 12, has 6 production units (shaded area), which are dashboard, transmission and engine manufacturers; interior, power train and final assemblers, and about 40 products, namely car, body, power train, etc.

Associated with product object is a component object, which is used for representation of Bill_of_Materials, which is a relationship between two product objects where one product object is a component of other product object. Since this relationship is one-to-many, one product object may have several components. For example, the car body depicted in Fig. 16 consists of 14 preformed tubes and 5 exterior sheets.

Associated with production unit are two object

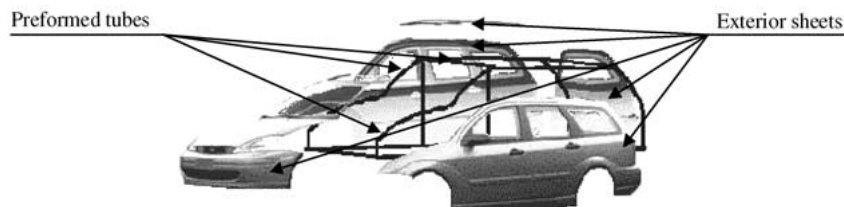


Fig. 16. Car body components.

classes (in the case of product, these objects actually represent relations): Production_Unit—Product relation and Production_Unit (Supplier)—Product—Production_Unit (Customer) relation. For example, for power train assembler and final assembler, following relationships exist: Power Train Assembler—Power Train, Final Assembler—Power Train, Final Assembler—Car, Power Train Assembler—Power Train—Final Assembler with various associated cost and time data as object properties.

A Production_Unit object owns resource object. Generic_Activity object, are associated with Production_Unit and deploy resource object, in implementing process object (associated with both product and resource objects). Also, relation between Generic_Activity objects at different levels of supply chain structure is represented, allowing creation of complex hierarchical structures of Production_Unit with ability to model different production structures as job-shops, assembly lines, cells, etc. (Chandra *et al.*, 2000).

5.3. Object-oriented model implementation of automobile supply chain data base

The implementation of a complex SC DCN network requires a database modeling technique that allows creation of data structures that can be flexibly mapped to object models. Accordingly, a flexible data modeling approach based on the DESO architecture (Smirnov, 1999) is utilized. This approach allows modeling any object structure with limited number of relations (tables). Figure 17 depicts five relations used in representing any relationship in the supply chain dynamic constraints network.

The above data structure is illustrated with the help of following example of creation of an automobile supply chain.

Steps involved in this process are:

(1) Create Class_and_Object: Classes supply chain and product are created in Table 2 along with instances of Objects for these classes. These are created as records in the table CLASS.

(2) Create Class_attribute: Attributes are added for these classes. Two attributes SC (which the product belongs to), and price are created for class product, as shown in Table 3.

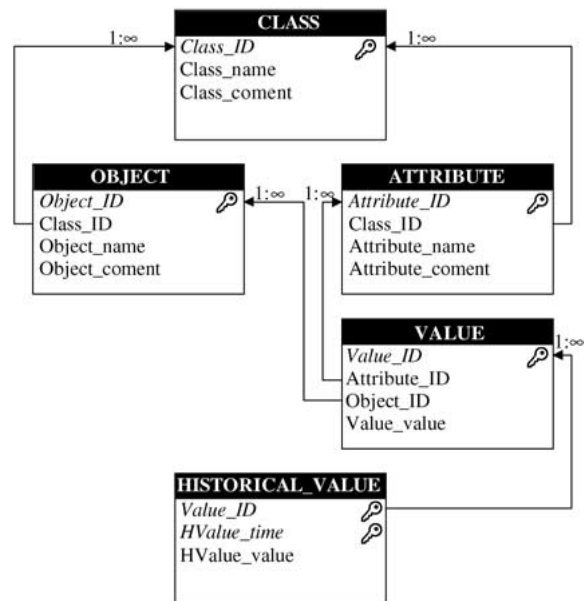


Fig. 17. A generic data structure schema for data modeling of supply chain dynamic constraints network.

(3) Create tuple (record) in Object: Records automotive SC, and car are created, as shown in Table 4.

(4) Create Values in relation (Table): Values for price attribute of car object are created, as shown in Table 5. For the first product attribute SC, a related record was created in VALUE table with SC Object_ID value being stored in the Value_Value

Table 2. Table of classes

Class_ID	Class_Name	Class_Comment
1	SC	Supply chain
2	Product	
3	Production unit	
4	Generic activity	
5	Resource	
6	PU-Product	Production Unit—Product Relation
7	PU-Product-PU	Production Unit (supplier)—Product—Production Unit (customer) Relation
8	Component	Product-Component Relation

Table 3. Table of attributes

Attribute_ID	Class_ID	Attribute_Name	Attribute_Comment
1	2	SC	Supply chain the product belongs to
2	2	Price	Product price
3	3	SC	Supply chain the production unit belongs to
4	4	Production unit	Production unit, generic activity belongs to
5	5	Generic activity	Generic activity, resource belongs to
6	6	PU	Processing unit, PU-product relation belongs to
7	6	Product	Product, PU-product relation belongs to
8	6	Holding cost	
9	7	PU_Supplier	Processing unit, which is a supplier in PU-Product-PU relation
10	7	PU_Customer	Processing unit, which is a customer in PU-Product-PU relation
11	7	Product	Product, PU-product-PU relation belongs to
12	7	Transportation cost	
13	7	Transportation time	
14	8	Product	Product, component belongs to
15	8	Component	Component of a product
16	8	Quantity	Quantity of component within product

Table 4. Table of objects

Object_ID	Class_ID	Object_Name	Object_Comment
1	1	Automotive SC	—
2	2	Car	—
3	2	Body	
4	3	Body manufacturer	
5	3	Car assembler	
6	4	Inbound activity	
7	4	Processing activity	
8	4	Outbound activity	
9	5	Assemble line	
10	6	Body manufacturer—body	
11	6	Car assembler—body	
12	6	Car assembler—car	
13	7	Body manufacturer—body—car assembler	
14	8	Car—body	Body is a component of a car

field. A slightly different situation is encountered with the second attribute—Price. Obviously, the price changes with time, thus, the HISTORICAL VALUE table to store all the history of price values is created, as shown in Table 6.

6. Conclusion

The universality of the knowledge representation by ontology-driven dynamic constraint networks for

supply chain models makes it feasible to provide powerful interactive tools for database and knowledge base maintenance. Knowledge management environment comprises means for supply chain ontology-oriented collaborative engineering. Ontology-based architecture supports co-operation among agents, thereby reducing time and increasing the quality of supply chain configuration process. Ontology-based knowledge management technology is an innovative technology in the supply chain domain. Using this

Table 5. Table of values

Value_ID	Attribute_ID	Object_ID	Value_Value
1	1	2	1
2	2	2	
3	1	3	1
4	2	3	
5	3	4	1
6	3	5	1
7	4	6	5
8	4	7	5
9	4	8	5
10	5	9	7
11	6	10	4
12	7	10	3
13	8	10	
14	6	11	5
15	7	11	3
16	8	11	
17	6	12	5
18	7	12	2
19	8	12	
20	9	13	4
21	10	13	5
22	11	13	3
23	12	13	
24	13	13	
25	14	14	2
26	15	14	3
27	16	14	1

technology enables improved decisions on supply chain configurations from supply chain unit templates, under constraints networks with reduced variance. Implementation of this technology will enable realise increased quality, reduced cost, reduced errors, decreased personnel requirements, and better supply chain configuration solutions.

Future plans for research on this topic are to develop and experiment generic supply chain network configurations based on, (a) divergent problem solving strategies, (b) functional or operational policies of Members and/or Group, and (c) levels of co-operation among members of the supply chain.

Acknowledgments

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Table 6. Table of historical values

Value_ID	HValue_Time	Value_Value
2	01/01/01 12:00	14,800.00
2	01/08/01 12:00	14,900.00
2	01/15/01 12:00	14,950.00
2	01/01/01 12:00	5,400.00
2	01/08/01 12:00	5,440.00
2	01/15/01 12:00	5,455.00
12	01/01/01 12:00	10.00
12	01/08/01 12:00	10.20
12	01/15/01 12:00	10.25
16	01/01/01 12:00	15.00
16	01/08/01 12:00	15.10
16	01/15/01 12:00	15.15
19	01/01/01 12:00	20.00
19	01/08/01 12:00	20.20
19	01/15/01 12:00	20.28
23	01/01/01 12:00	120.00
23	01/08/01 12:00	120.50
23	01/15/01 12:00	121.00
24	01/01/01 12:00	24
24	01/08/01 12:00	24
24	01/15/01 12:00	24

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