A hierarchical model for e-supply chain coordination and optimisation

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Abstract

Purpose – The integration of e-business and supply chain enables seamless information flow from suppliers to customer service network via the internet. It also enables better-coordinated materials flow from customer order to production, storage, distribution and delivery. The purpose of this paper is to describe the work that leads to the realisation of a hierarchical model for e-supply chain coordination and optimisation.

Design/methodology/approach – The model is based on an e-business information flow network in order to respond rapidly to the dynamics of e-supply chain and market. It can be used to realize management level strategies, and facilitate the planning and control of detailed operation schedules of supply chain units in an e-supply chain environment. Three main modules are discussed. They are routing and sequence optimiser (RSO) with the aid of a GA and TS-based multiple population search strategy (MPSS); supply chain virtual clustering (SCVC) based on fuzzy virtual clustering; and supply chain order scheduling (SCOS) using an agent-based distributed scheduling system.

Findings – These modules enable: the generation of preferred routings, transportation modes and work order plan under such constraints as customer service level, cycle time and cost; the formation of supply chain's unit-transportation-work order families using a clustering approach to down-size supply chain problems and increase computation efficiency; and the integration of scheduling with supply chain optimisation in order to facilitate the control of a supply chain with the aid of an agent-based distributed scheduling approach.

Originality/value – This paper proposed a hierarchical model for e-supply chain coordination and optimisation that is capable to solve large-scale problems. A MPSS using GA and TS was depicted in detail to expedite the RSO.

Keywords Supply chain management, Electronic commerce, Algorithmic languages

Paper type Research paper

1. Introduction

Information and communication technology, which brings about e-business, has created much impact on almost every sector of the society in recent years. The emergence of e-business has advanced the application of supply chain management (SCM) to e-manufacturing and brings about global manufacturing. Conversely, recent review shows that global manufacturing has increased the complexity of SCM, and supply chain coordination and optimisation have become essential elements of manufacturing strategy. Thus, organizations have moved from centralized, vertically integrated, single-site manufacturing facilities to geographically dispersed networks of resources that collectively create value for customers. These extended enterprises may be consonant with a single multinational organization or, as is increasingly the case, a set of strategically aligned companies to capture specific market opportunities.

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They are designed to provide the speed and flexibility necessary to respond rapidly to windows of market opportunity.

Traditional supply chain practices and technologies that integrate productive and logistical activities within a company are necessary but not sufficient for competitive success. New supply chain practices and technologies such as e-business and e-manufacturing, must now link production and logistics processes in different organizations across geographically dispersed locations. Examples of organisations that have employed new supply chain practices to improve their competitiveness include Hewlett-Packard, IBM, Chrysler, Lear, AlliedSignal, and Wal-Mart (Stock *et al.*, 2000). The so-called e-business enabled supply chain, or e-supply chain management, is an emerging manufacturing and business strategy that enables the power of e-business to be integrated with manufacturing operations and various supply chain units through the use of internet and other tether-free technologies (Luo *et al.* 2001a, b). It accelerates product realisation, manufacturing and delivery, and results in a shorter product cycle time, lower cost, better response to customer needs and improved customer services.

2. Moving towards a hierarchical coordination and control of supply chains

The integration of e-business and supply chain requires information in the entire supply chain to be linked. In so doing, it enables a smooth information flow from suppliers to customer service network through the internet, tether-free technologies and computational tools (Wohlwend and Fulton, 2005; Cheng and Lin, 2004; Lee, 2003). Such an e-business information flow network lays the foundation for a better-coordinated material flow network from customer order to production, storage, distribution and delivery (Figure 1). It is possible for demand data as well as supply, inventory and manufacturing capacity data to be made visible to all companies within a manufacturing supply chain. However, the dynamics of the enterprise and the market make the planning and control of the supply chain difficult even with the help of the above-mentioned information flow network.

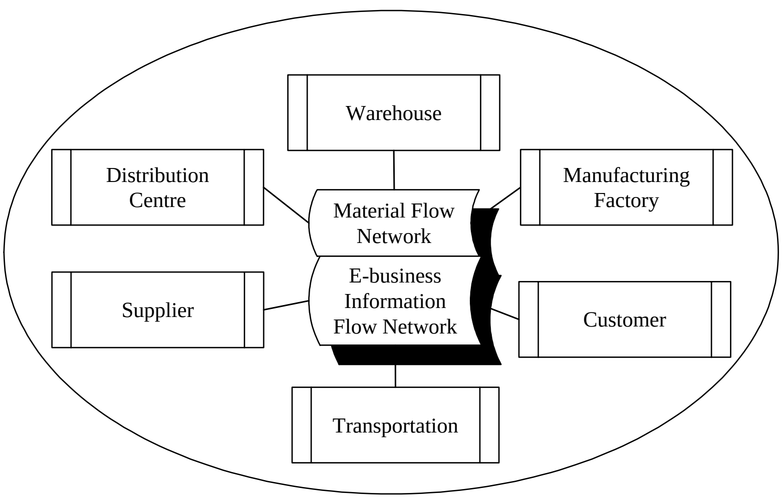

Figure 1.
Framework of an e-supply chain

Many researchers (Luo *et al.*, 2001a; Ettl *et al.*, 2000) attempted to integrate various functions of an enterprise. Software agents (Dumond and Roche, 2000), Petri nets and graph (Khoo and Yin, 2003; Raghavan and Viswanadham, 1999), dynamics modelling, blackboard-based system (Ito and Salleh, 2000), and simulation (Archibald *et al.*, 1999) were used to deal with various supply chain problems. From the review, it has been established that much work has been done in supply chain design, restructuring and functional optimisation. These include optimisation of the location of facilities, transportation and inventory so as to bridge the gaps among the various functions of a supply chain and the gap between theory and practice. It appears that most researchers focus on strategic issues such as:

- preservation and development of internal activities (Huiskonen and Pirttila, 2002);
- the relationship among demand, inventory level and customer service level (Ettl *et al.*, 2000); and
- restructuring of supply chain to maximise its profit (Hwang, 2002).

2.1 Planning, control and operation schedule

More recently, researchers began to explore the possibility of integrating manufacturing planning and control with supply chains as the variation in factory schedule might adversely affect the overall performance of supply chains. In recent years, companies such as Dell do not carry large inventory. They receive orders from clients, purchase components from external suppliers, assemble components and deliver products to clients. Manufacturing of products and their distribution to clients concern:

- delivering products in time;
- minimising inventories;
- reducing production cost; and
- achieving certain customer service level.

The impact to the overall responsiveness of a supply chain cannot be addressed effectively and efficiently without a powerful supply chain planning and control system. Thus, it is necessary to introduce a mechanism that can better use the e-business information flow network, share production plans and capacity of the entire supply chain, and allow each supply chain unit to collaborate instead of trying to optimise locally the individual processes at every stage.

The works of Mentzer (2001) and Luber (1991) revealed that lead-time was widely used to estimate the processing time and transition time. Most of the work surveyed thus far does not possess the ability to estimate the actual loading of a manufacturing plant. As a result, the lead-time assigned is usually much longer than necessary so as to ensure smooth operation. This may result in higher inventory level as well as cost. It is obvious that adopting a holistic approach to planning and scheduling is becoming more and more important for the purpose of achieving global optimisation and coordination of supply chains. For example, production facilities often have more complex resource constraints than other units in a supply chain. Sharing of the information about resource constraints of production facilities will facilitate the planning and scheduling of other supply chain units. In this respect, a generic model that supports the hierarchical coordination and optimisation of supply chains, and a holistic approach to the scheduling and planning of supply chains becomes necessary.

Griffiths and Margetts (2000) managed to illustrate how variation in production schedules could affect the supply of parts, even though the purpose of their works were not targeting at the needs to integrate scheduling with supply chain. Lendermann *et al.* (2001) attempted to improve the accuracy of supply chain simulation by embedding a so-called advanced planning and scheduling procedure to realize a leaner and more responsive supply chain. From their work, it is apparent that detailed schedule is important to SCM and optimisation. Reis *et al.* (2001) presented a multi-agent cooperative scheduling system for an extended enterprise. The system embodied a model for dynamic production scheduling. It came with a mechanism, which allowed a group of cooperative scheduling agents to derive the schedule through physical or virtual coordination of agents. It avoided scheduling/rescheduling solutions that could appear locally feasible, and only a feasible solution was offered to the enterprise. Resource constraints such as tooling were difficult to incorporate due to the restriction imposed by the system. Various models, including MIP (Leung *et al.*, 2002), 0-1 programming (Hwang, 2002), petri nets (Raghavan and Viswanadham, 1999), and nonlinear model (Ettl *et al.*, 2000) were used to simulate the simplified supply chain systems. Functional optimisation is of great value to an enterprise. It provides basic strategies to assist suppliers and customers, so as to ensure a sufficient materials or product flow to manufacturing sites in time or to customers with a promised customer service level. However, most of the work done so far were at management level to facilitate decision-making or were targeted for a unique problem. Thus, adapting them to handle other problems may be difficult. Some of the models were static and over-simplified as reducing the number of decision variables in order to speed up problem-solving was the main concern. For instance, capacity limitation was removed; stationary demand was used in the work of Graves *et al.* (1998) where highly simplified production process and elimination of internal stock-out were used; and a two-stage (inventory-transportation-customer) supply chain was considered in the work of Geunes and Zeng (2001) while ignoring other supply chain units. Thus, in order to analyze and coordinate the planning and scheduling of an entire supply chain, a comprehensive representation is necessary. This representation should be able to provide an enabling infrastructure, which is generic, flexible and sophisticated enough to incorporate important supply chain features such as hierarchical structure, various modes of transportation, multiple level split, merge and assembly, and cross-boundary representation, in order to promote supply chain coordination and global schedule optimisation. While governed by higher-level decisions, findings and objectives, the solutions from the lower level comply more with the global objectives.

2.2 Solving large-scale problems

A supply chain especially e-business enabled supply chain, i.e. e-supply chain, might be enormous in terms of the number of supply chain units, and complex. In reality, a supply chain may have multiple end products with shared components, facilities, capacities and suppliers. The flow of materials is not always along an arborescent network. Hence, this would further increase the size of the problem. The model described by Luo *et al.* (2001b) considered an e-supply chain to possess Tiers I and II suppliers, and de-manufacturing, which disassembles the product and forwards the recovered materials or components to suitable supply chain stages. It is noted that their model cannot deal with planning and scheduling. Furthermore, the optimisation approach adopted can only be used to handle simple problems. To deal with a sizable supply chain that may grow beyond the ability of existing optimisation approaches to cope, a more robust methodology is thus necessary. It is envisaged that clustering technique, which is able to decompose a complex problem into smaller and controllable ones, would help in reducing the search space and improving the efficiency of the search procedures to derive better solutions for the entire supply chain. In this respect, group technology (GT), which was first postulated by Burbridge (1975), can possibly be adapted. Basically, GT is a technique that can be used to identify and group together similar parts and manufacturing operations or processes into families during all stages of design and production (Khoo *et al.*, 2003). For example, a family of parts is made up of components that can be manufactured by similar machinery, tooling, machine operations, and jigs and fixtures. After part families are formed, machines are often organised into manufacturing cells and the families of parts assigned to cells according to their routings. It is envisaged that the basic principles of GT can be borrowed and enhanced using such technique as fuzzy sets theory and graph theory to realize a comprehensive model or representation for the handling of e-supply chain problems. In so doing, a complex supply chain model can possibly be decomposed into supply chain clusters comprising supply chain units, transportation modes and work orders.

2.3 Supply chain coordination

The revision of plans or schedules in a supply chain needs proper coordination. Any slip in the coordination may lead to immediate and tangible losses. Thus, the agility with which a supply chain is managed at tactical and operational levels will have an impact on the way in which enterprise goals are achieved. Research effort in this area, however, seems lacking. Furthermore, the individually optimised solution of a single manufacturing plant or a supply chain unit may turn out to be unfavourable to the global objectives and may even jeopardize the performance of the entire supply chain. This provides the motivation for the authors to investigate into an intelligent decision-making mechanism to facilitate the exchange of information and promote negotiation and coordination among the various supply chain units. It is envisaged that such an intelligent mechanism would help in realizing a globally optimised schedule for a supply chain.

3. A hierarchical model for e-supply chain coordination and optimisation

As mentioned in Section 2, in order to provide an enabling infrastructure, which is generic, flexible and sophisticated enough to incorporate important supply chain features so as to promote supply chain coordination and derive a near global optimised plan and schedule, a distributed hierarchical model of a supply chain is fundamental and critical. Here, a framework for supply chain optimisation, which supports the hierarchical coordination and optimisation of the entire e-supply chain, is proposed.

As shown in Figure 2, supply chain optimisation and management have different levels, from strategic and long-term, such as supply chain design, modelling and simulation, to operational but short-term levels, such as production scheduling. It has been established in Section 2 that the integration of planning and scheduling with supply chain optimisation is a difficult task. The necessity of carrying out such a task includes:

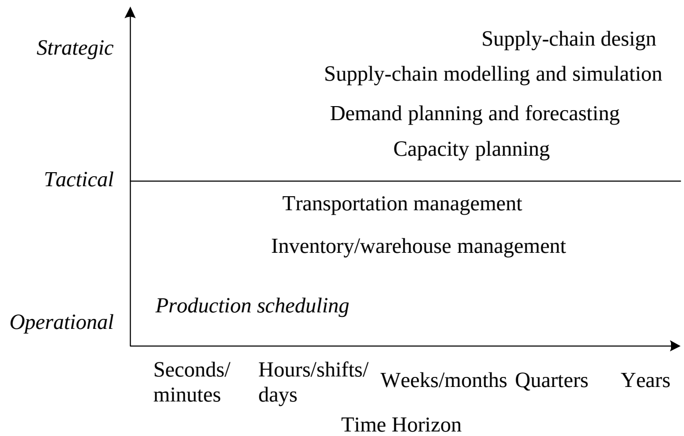

Figure 2.
Different level of supply chain management

- Long-term management objectives usually conflict with operational objectives. For example, manufacturing operations may attempt to maximise the throughput and lower cost, while this may directly affect the inventory level and increase the inventory level of downstream operations. Minimising inventory level is a long-term management objective, which contradicts maximising manufacturing throughput in this case.
- Supply chain units traditionally operate independently. The mechanism to promote the integration and coordination currently is still at strategic level (Lendermann *et al.*, 2001). Effective coordination and integration at operational level are much more difficult due to the complexity of communication, information sharing and shielding, searching for a global feasible or optimal solution.
- A supply chain especially an extended one, which includes suppliers' and customers' supply chain networks, might be enormous in terms of the number of supply chain units. This drastically increases the complexity and decreases the efficiency of the coordination.

This paper attempts to address the above by examining issues concerning scheduling and supply chain optimisation. It includes the realization of a hierarchical model for supply chain coordination and optimisation along the entire supply chain units, such as suppliers, manufacturing plants, warehouses, distribution centres and customers. It possesses the ability to support an extended supply chain environment, which takes into consideration suppliers' and customers' supply chain networks.

3.1 A framework

In order to achieve a seamless integration of scheduling for supply chain optimisation, a distributed intelligent coordination and scheduling system that is able to support materials flow network within an e-business environment is necessary. Such a system would help in resolving the conflicts among the requirements of supply chain units. The framework of a prototype system is shown in Figure 3. The prototype system comprises three main modules namely routing and sequence optimiser (RSO), supply chain virtual clustering (SCVC) and supply chain order scheduler (SCOS). Essentially, the SCOS is

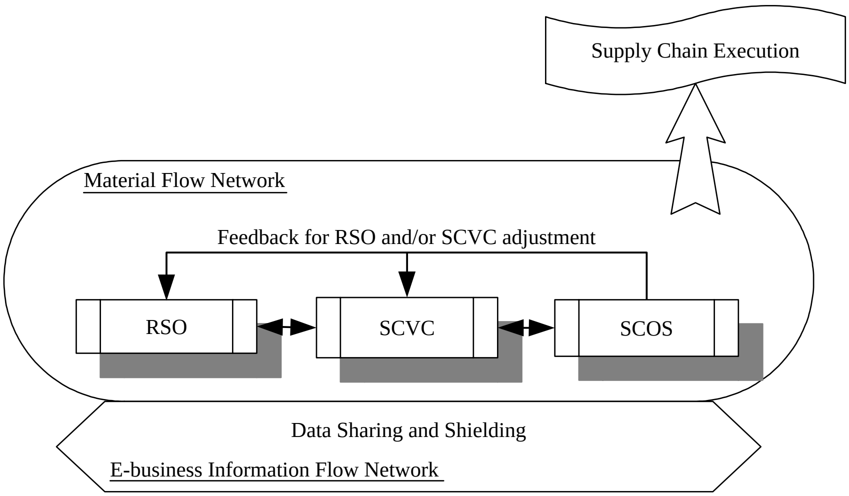

Figure 3. Framework of the proposed system

controlled by the SCVC to compartmentalize a complex supply chain optimisation problem that can hardly be solved by conventional algorithms due to combinatory explosion. In order to reflect the strategies at management level, the RSO takes into account business strategies, customer requirements, and the capacity of supply chain units to generate a preferred set of routing and work order process sequence.

Briefly, sales and marketing data, such as customer orders, which are gathered by marketing personnel, and the detailed information about the supply chain units, such as status, capacities and topology, are forwarded to the prototype system for processing. The prototype system then invokes the RSO to generate the preferred routings, transportation modes and work order plan based on the constraints of customer service, cycle time and cost. Subsequently, it forwards the suggested routings, transportation modes and work order plan information to the SCVC. In order to efficiently derive near optimal solutions for the entire supply chain, the various supply chain units, transportation and related customer orders are virtually and dynamically organised into different supply chain's unit-transportation-work order families based on some similarity measures. A work order family can then be processed totally within a unit-transportation family. This compartmentalizes a supply chain problem into sub-problems so as to reduce its search space and expedite flow planning and scheduling using the SCOS. The SCOS generates a near-optimal schedule for each of the unit-transportation family and subsequently combines them into a schedule for the entire supply chain with the assistance of a scheduling engine. It is supported by a distributed and intelligent mechanism to exchange information and promote negotiation, and coordination within or among the unit-transportation families. The detailed schedule is then examined and fine-tuned based on a compliance measure using the feedback information from the SCOS to the SCVC, and the RSO.

Basically, the solution from the preceding higher-level module provides the inputs or constraints for the succeeding modules to comply. Here, a so-called compliance measure, which is the degree (in percentage) in which the solution generated by a module complies with those derived by higher-level modules, is used to evaluate the performance of all the modules and fine-tune the detailed schedule of the SCOS. With such a framework, the long-term management objectives can be modelled into the RSO for routing and sequence selection which guides the other two modules, SCVC and SCOS. Since, a large-scale supply chain optimisation problem has been compartmentalized into sub-problems by the SCVC, the search procedure of the SCOS to reach a near-optimal schedule for the entire supply chain can be expedited.

4. Routing and sequence optimiser

A work order may have multiple routings that denote the flow of materials, i.e. materials flow. Basically, materials flow captures the sequence in which materials move from suppliers (raw materials) to manufacturers (finished product), and to customers (delivery) as shown in Figure 4. For each routing of a work order, it may use different materials (Figure 5) and go through different manufacturing plants. For this reason, a work order may have different cycle time, different cost and delivery date when applying different routings. In summary, these routings have different:

- materials/manufacturing/transportation/inventory/delivery cost;
- delivery date; and
- cycle time; and so on.

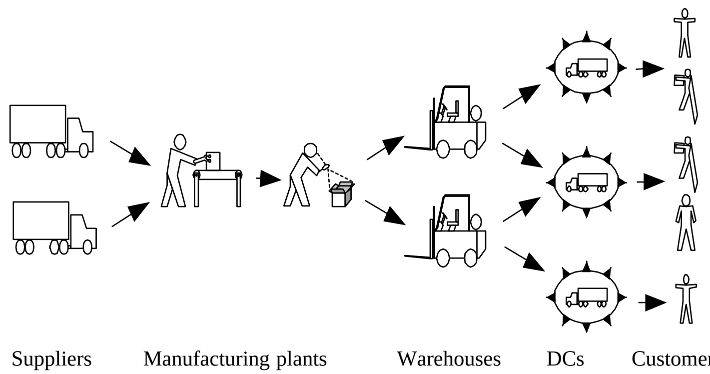

Figure 4.
Materials flow network

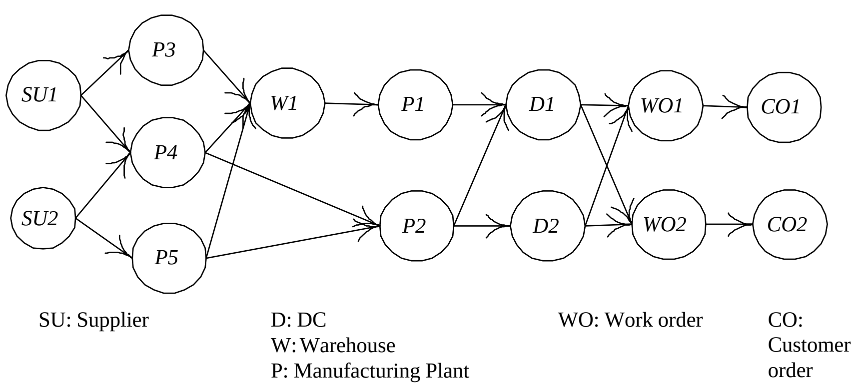

Figure 5.
Multiple routings of a typical supply chain

Since, the capacity of each supply chain unit such as a manufacturing plant is limited, a near optimal routing and a work order process sequence are necessary for a mixture of work orders and products. Furthermore, management level strategies can be incorporated into the prototype system. By selecting a proper combination of routing and work order process sequence, better plans can be generated for the entire supply chain, which is effective in maintaining or even increasing customer service level, reducing inventory, transportation and production costs, and lowering the safety stock level.

4.1 Multiple population search strategy for RSO

This module focuses on routing selection for work orders, and optimising work order sequence using such approaches as genetic algorithms (GA), tabu search (TS) and a combination of GA and TS. Essentially, GA (Holland, 1975) is a technique that is easy to use and can be applied to solve a wide range of optimisation problems. However, most of the GA applications require fine-tuning of GA parameters in order to achieve good results. The TS algorithm, on the other hand, was developed independently by Glover for solving combinatorial optimisation problems. It is a kind of iterative search. It adopts a flexible memory or tabu list, which is able to help eliminate and search beyond the local minima. In this work, a new hybrid heuristic, which integrates GA and TS for solving RSO problems, has been developed.

As shown in Figure 6, TS is embedded into the GA to implement the multiple population search strategy (MPSS) that is able to facilitate the search process, help determine the GA parameters and produce next generation chromosomes, and avoid premature convergence. GA parameters are very important to the performance of GA. A good parameter set improves the chance for an algorithm to obtain the near global optimal solution. However, since the mathematical foundation of the GA is weak, deterministic method for the selection of GA parameters does not exist. As two important control parameters, crossover and mutation rates affect the performance of GAs drastically. It usually takes a lot of trial-and-error attempts with various combinations of GA parameters in order to find good parameters and achieve good results for a particular problem. In order to overcome this weakness, a novel approach that embeds the TS into the GA procedure is proposed in this work to dynamically search for better GA parameters within a GA run. Multiple populations with different GA parameters are maintained in a GA run. These populations, which are treated as individuals in a TS, reproduce themselves from generation to generation concurrently using genetic operators. At the end of each parameter updating iteration (i.e. the number of GA generations), a promising level for each parameter set, which is given by the fitness value attained by the objective function during the TS, is calculated. The best parameter set in terms of promising level is then selected. From the TS point of view, the GA run is used to evaluate the objective function (i.e. the promising level) of the parameter set. The multiple populations provide the individuals in the TS. For example, for every five generations of GA runs, the promising level of each parameter set of the population is evaluated and used as the value attained by the objective function for the selection of the best parameter set. The neighbouring parameters of the best parameter set is then created and assigned to the new populations of the succeeding GA run.

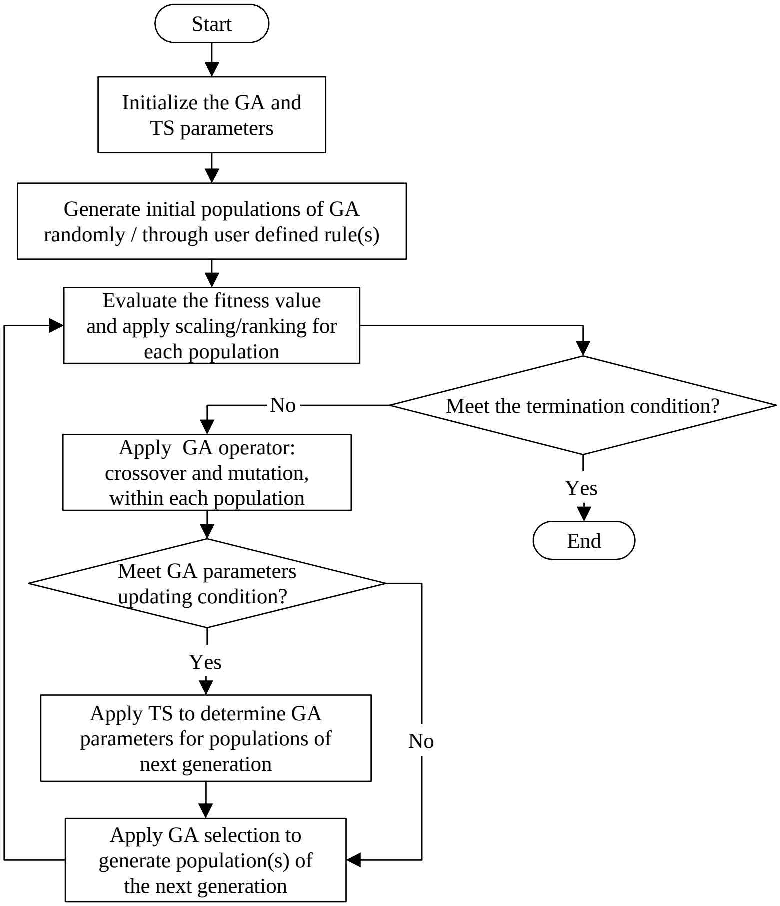

Figure 6.
Flow chart of the proposed algorithm for routing and sequence optimisation

4.2 Results and discussions

Two types of simulation runs, namely a basic GA simulation (SIM 1) and a TS enhanced GA-based MPSS (SIM 2), have been performed. The parameters for each of the simulation runs are summarised in Table I.

The comparison is based on the mean fitness value and the best individual in each generation of the 20 simulation runs. It can be derived using equations (1) and (2):

$$F_i^- = \frac{1}{n}\sum_{j=1}^{j=n} \bar{F}_{ij} \tag{1}$$

$$F_i^* = \frac{1}{n}\sum_{j=1}^{n} \min(F_{ij}) \tag{2}$$

where n, the number of simulation runs for SIM 1 or SIM 2. Here, it is 20. F_{ij}, the fitness value of generation i of simulation run j of SIM 1 or SIM 2. $\bar{F}_{ij}$, Mean fitness value of

Parameters	SIM 1: basic GA	SIM 2: MPSS
Number of simulation runs	20	20
Number of generation for parameter updating	N/A	10
Generation of new population	N/A	Random selection plus elitist 30 percent
Number of populations	1	4
Number of GA generation	100	100
Population size	200	50
Initial crossover rate	0.8	0.9
Initial mutation rate	0.005	0.01
Elitist strategy (percentage of the best individual to be selected)	8	8
Crossover rate step length ($s_c^{\max}/s_c^{\min}$)	N/A	0.2/0.01
Mutation rate step length ($s_m^{\max}/s_m^{\min}$)	N/A	0.05/0.001
Weight of delivery on time	2	2
Weight of order cost	1	1
Length of tabu list of GA parameters	N/A	5

Table I.
Parameter setting of SIM 1 and SIM 2

generation i of simulation run j of SIM 1 or SIM 2. F_i^-, mean fitness value of generation i of simulation runs of SIM 1 or SIM 2. F_i^*, the best fitness value of generation i of simulation runs of SIM 1 or SIM 2.

The standard deviation of the mean fitness values attained by SIM 1 and SIM 2 is shown in Figure 7. It is apparent that the variation of the individuals of the MPSS is smaller than that of the basic GA. This also implies that the MPSS converges faster with the first five generations showing contradictory trend that are caused by the initial rule applied.

Figure 8 shows the absolute difference of the best fitness value of each generation among all the simulation runs. Apparently, the MPSS outperforms the basic GA. During the simulation runs, the MPSS reaches the best solution, which has a fitness value of 4,697 at generation 35, while the basic GA reaches the same solution at generation 50. It is indicated by the big gap located between generations 30 and 50

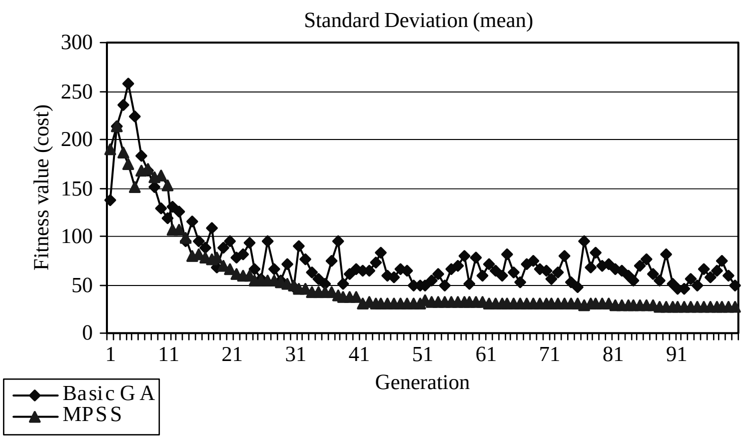

Figure 7.
Standard deviation of mean fitness value F_i^- of SIM 1 and SIM 2

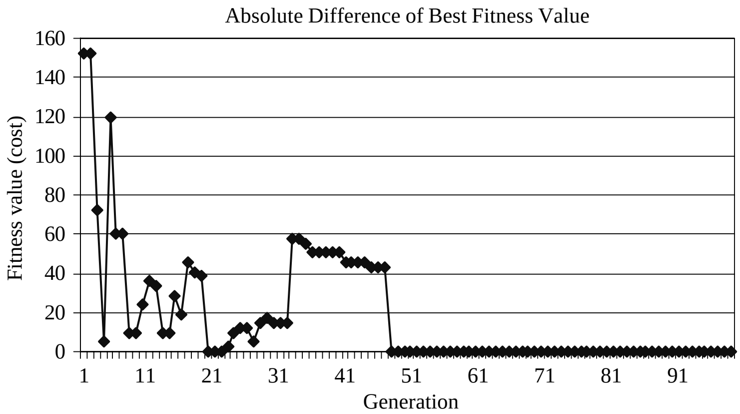

Figure 8.
Absolute difference of the best fitness value of SIM1 and SIM2

in Figure 8. It is obvious that the MPSS obtains the best solution much more quickly than the basic GA due to the optimised crossover and mutation rates.

5. Supply chain virtual clustering

A number of techniques can be used to solve clustering problems. These include matrix formulation, graph theory and artificial intelligence (AI). These techniques possess good potentials to be employed for the identification of virtual unit-transportation-work order families. As discussed in Section 2, a comprehensive representation and a hierarchical model of a supply chain is fundamental and critical to incorporate the multiple level decision-making and optimisation.

Typically, in optimising a supply chain, customer orders, product flows, supply chain units, transportation, customer service level, and other resources and constraints are used as inputs to a simulation program, an optimisation program or a heuristic rule-based engine so as to derive a product plan or recommendations of inventories. As already mentioned, a complex e-supply chain optimisation problem can hardly be solved by traditional GAs due to combinatory explosion. An approach based on virtual clustering is proposed here to reduce the search space. The approach is likely to help derive the near optimal or at least good-enough solutions for a complex supply chain efficiently. The supply chain units, transportation and customer orders as shown in Figure 9 can be virtually and dynamically organised into different unit-transportation-work order families based on some similarity measures before optimisation. A work order family can then be processed totally within a unit-transportation family. Computational efficiency can be improved as a large-scale supply chain optimisation problem has been compartmentalized into relatively small sub-problems.

Similar to GT in part classification, similar supply chain units and work orders can also be grouped into a family based on their characteristics, that is, similarity measures, such as routings, due date and priorities of work orders, loading of a manufacturing plant and/or the location of the customer and the distribution centres.

To guide the process of virtual clustering, the criteria to determine the similarity of supply chain units, transportation and work orders are listed as follows:

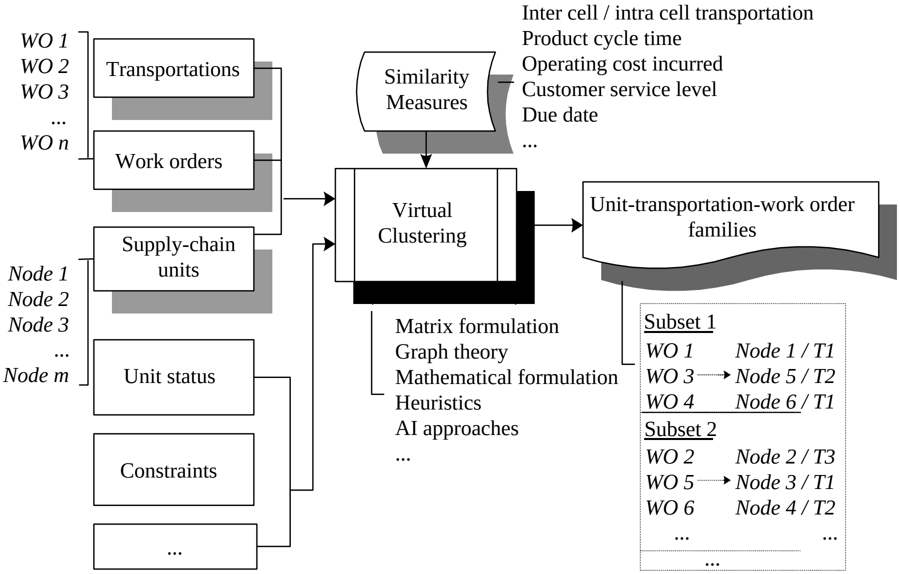

Figure 9.
Process flow of virtual clustering

- inter cell/intra cell transportation;
- product cycle time;
- operating cost incurred;
- transportation cost;
- customer service level;
- balance loading of supply chain units; and
- due date.

After determining the unit-transportation-work order families by the proposed virtual clustering approach, work orders are simply processed and optimised within the respective families. This helps in speeding up the distributed planning and scheduling process. The above-mentioned virtual clustering approach has the following characteristics:

- Compartmentalize a supply chain problem into sub-problems so as to decompose a complex problem into a number of manageable and small problems. This will expedite flow planning and scheduling. Although a trade-off between the speed of the optimisation and the quality of the results may exist, by using an appropriate similarity measure, it is possible to derive a near global optimal or "good-enough" solution.
- Help to split a supply chain optimisation problem purposefully instead of blindly so that it can be run on multiple distributed computers concurrently with less interference.
- Use as a plug-in and can be easily integrated with existing supply chain optimisation systems.

5.1 Virtual clustering using fuzzy set

Fuzzy set theory can be used to measure and express the fuzziness in a system. Unlike conventional set theory, it allows elements to be partially belonging to a set. Each element is given a membership value, which can range from 0 (not belong) to 1 (belong). Basically, a membership function expresses the relationship between an element and its membership to a fuzzy set. Techniques such as fuzzy single linkage clustering, fuzzy rank order clustering, fuzzy C-means clustering, fuzzy mathematical programming and fuzzy-neural methods have been widely used to tackle clustering problems.

In this work, fuzzy set theory is used to facilitate virtual clustering of supply chain. Figures 4-10 shows the main components of the proposed approach:

- *Data inputs*. It comprises supply chain units, customer orders/work orders and transportation modes. Other constraints such as regional restrictions can be introduced as part of the model.
- *Clustering engine*. Different combinations of similarity measures, including inter/intra cell transportation, product cycle time and operating cost, can be used to determine grouping patterns. The similarity of each supply chain units-transportation-work order family can then be evaluated so as to guide the search to derive a near optimal or at least a good-enough solution. Heuristic procedures for local search such as GAs and TS are used to determine the fuzzy cluster matrix.
- *Outputs*. The unit-transportation-work order families obtained are used as the input for the SCOS.

6. Supply chain order scheduler

A supply chain has various customer requirements and multiple end products with shared components and capacities. In order to fulfil customer order, materials and components from suppliers are transformed into final products by manufacturing and assembly plants, distributed to warehouses and distribution centres and finally

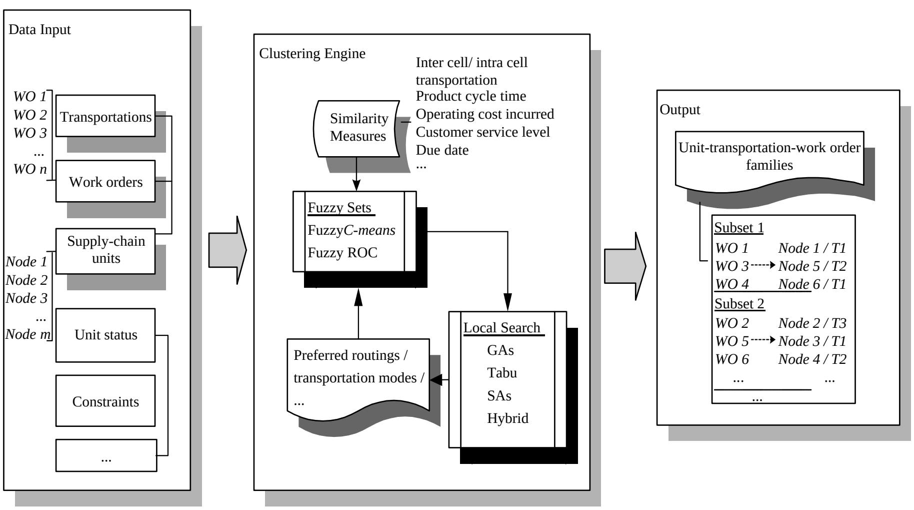

Figure 10.
A fuzzy set-based virtual clustering

delivered to customers. The optimal schedule of an individual supply chain unit may contradict the requirements of other units and even deteriorate the overall performance of the entire supply chain. In order to handle such complex scheduling problems within an e-supply chain environment, a distributed intelligent coordination and scheduling mechanism is therefore necessary (Khoo *et al.*, 2001).

In this work, an overall architecture for an agent-based distributed scheduling system (ADSS) for e-supply chain is proposed and implemented. The ADSS consists of two subsystems, the supply chain scheduling master (SCSM) and the supply chain scheduling client system (SCSC). The SCSM maintains all the domain knowledge and scheduling information in its database and communicates with all the SCSCs, which represent the supply chain units in the e-supply chain environment. The SCSM also provides a negotiation locale for the supply chain unit agents to resolve any conflicts among local optimised schedules when they try to obtain the near optimal schedule for the entire supply chain. Basically, the ADSS is supported by and built on top of the e-business information flow network, which enables the communication and coordination of geographically dispersed networks of resources. The SCSC works out the local near-optimal shop floor schedule by retrieving the necessary information from the SCSM. The ADSS is built on top of an existing GA-enhanced dynamic scheduler by which the near-optimal local schedules are derived (Khoo *et al.*, 2000). Figure 11 shows the overall architecture of the ADSS.

Two types of agents are deployed, namely the supervisory agent of SCSM and the supply chain unit agent of SCSC. The roles and functions of the supervisory agent and supply chain unit agent are described as follows.

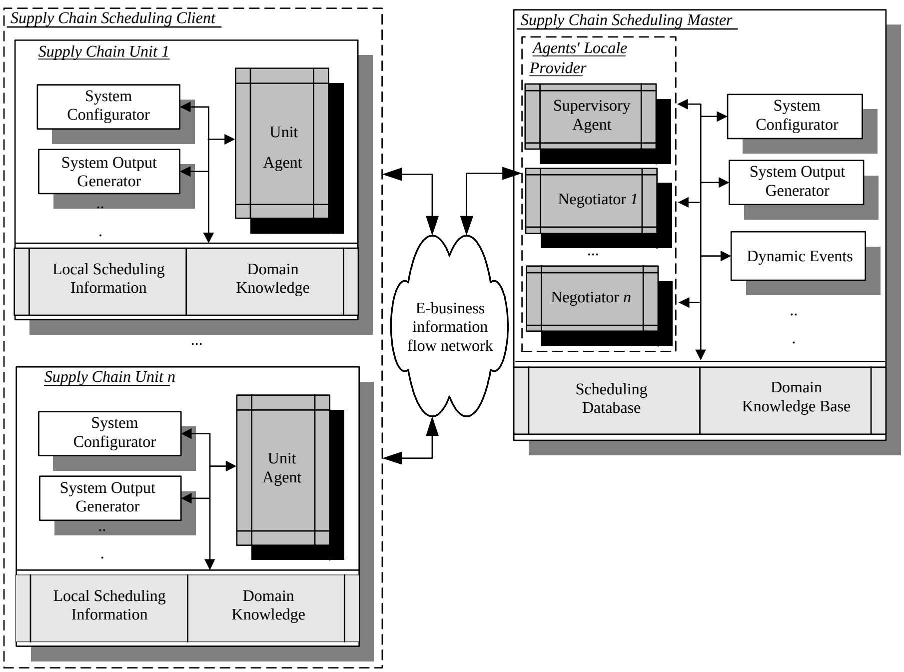

Figure 11.
An overall framework of an agent-based distributed scheduling system

6.1 Supervisory agent

The supervisory agent is the *de facto* manager of the software agents. The priorities of the negotiators are assigned by a decision-making module which utilizes the rules stored in the knowledge base. The local schedules obtained are compared pair-wise to check for potential conflicts, which can be resolved using the rules stored in the knowledge base. The supply chain unit agents reschedule the local schedules. The entire cycle repeats itself until a conflict-free schedule for the supply chain is obtained.

6.2 Supply chain unit agent

As the supply chain environment is not static, dynamic events often render a schedule sub-optimal or infeasible. Algorithms for handling dynamic events are therefore incorporated into the dynamic scheduler of the supply chain unit agent.

Once a supply chain agent or the negotiator receives a re-scheduling instruction from the decision-making module of the SCSM, it will activate the dynamic scheduler of the supply chain concerned to reschedule according to the prevailing set of new constraints.

After the dynamic scheduler has completed scheduling a specific supply chain unit, the various scheduling attributes, such as the number of jobs, the start/end time of jobs, the due date of jobs and so on, are then forwarded to the relevant negotiator. The local schedule is simultaneously dispatched to the scheduling database in the SCSM. In this way, the SCSM provides a locale for negotiation and decision-making. Thus, complex scheduling problems may be decomposed into sub-tasks, which can be handled at the supply chain unit level using local computers. A distributed agent-based approach to the scheduling of an entire supply chain is thus established.

7. Conclusions

The proposed e-business information flow network that is derived from the integration of e-business and supply chain enables seamless information flow from suppliers to customer service network via the internet. It provides the basis for a better-coordinated materials flow network from customer order to production, storage, distribution and delivery. The dynamics of enterprise and market make the planning and control of supply chains difficult even with the help of the above mentioned information network. Thus, it is necessary to realize a mechanism that is able to take advantage of the e-business information network, share production plans and capacity of the entire supply chain, and allow each supply chain unit to collaborate instead of optimising locally individual processes at every stage.

In order to address the above-mentioned issues, a hierarchical model for e-supply chain coordination and optimisation is proposed. The hierarchical model, which comprises three modules namely RSO, SCVC and SCOS, can be used to facilitate planning and optimise the detailed schedules of various supply chain units such as manufacturing plants, suppliers, warehouses, distribution centres and customers. The work also reveals that:

(1) With the aid of a GA and TS-based MPSS, the RSO is capable of generating preferred routings, transportation modes and work order plan under the constraints of customer service level, cycle time and cost.

(2) With the introduction of the so-called supply chain's unit-transportation-work order families using fuzzy virtual clustering, the SCVC is able to:

- down-scale supply chain problems;
- split a supply chain optimisation problem so that it can be run on multiple computers concurrently;
- help to speed up the search procedure; and
- use as a plug-in for existing supply chain optimisation systems.

(3) By introducing an agent-based distributed scheduling system (ADSS) which is supported by and built on top of the e-business information flow network that enables the communication and coordination of geographically dispersed networks of resources, integration of scheduling with supply chain optimisation is achievable.

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