Flex Serv Manuf J (2010) 22:183–213
DOI 10.1007/s10696-011-9082-7

Collaborative fractal-based supply chain management based on a trust model for the automotive industry

Seungjin Oh · Kwangyeol Ryu · Ilkyeong Moon · Hyunbo Cho · Mooyoung Jung

Published online: 22 February 2011

Abstract In the supply chain of the automotive industry, where the procurement ratio of parts from partners is very high, the trustworthiness of partners should be considered during supply chain optimization. In this paper, to deal with the trust issue related to collaboration and reduce the computational load in production planning, we develop a collaborative fractal-based supply chain management framework for the automotive industry. In our framework, the relationships between the participants of a supply chain are modeled as a fractal. Each fractal has a goal model and generates a production plan of its participants based on the goal model. The goal model of each fractal is developed from an operational perspective to consider the trust value of participants during production planning. A fuzzy trust evaluation model is used to evaluate the trust value in terms of numerical value. To validate the developed framework in the automotive industry, simulations are conducted. The results of the simulations indicate that our framework can be useful in generating precise production plans.

S. Oh · H. Cho
Department of Industrial and Management Engineering, POSTECH, Pohang 790-784, Republic of Korea
e-mail: halmea@postech.ac.kr

H. Cho
e-mail: hcho@postech.ac.kr

K. Ryu (✉) · I. Moon
Department of Industrial Engineering, Pusan National University, Busan 609-735, Republic of Korea
e-mail: kyryu@pusan.ac.kr

I. Moon
e-mail: ikmoon@pusan.ac.kr

M. Jung (✉)
School of Technology Management, UNIST, Ulsan 689-798, Republic of Korea
e-mail: myjung@unist.ac.kr

Keywords Supply chain management · Automotive industry · Trust evaluation · Collaborative fractal-based supply chain management (*c*-*f*SCM)

1 Introduction

Recent trends emphasize collaborative and agile supply chain management to manage the uncertainties and dynamics of the global marketplace (Buzacott and Mandelbaum 2008). The automotive industry, especially, pays considerable attention to collaborative supply chain management, because it is faced with diverse dynamics such as globalization, outsourcing, product variants, and risks of supplier disruption. An automobile is composed of about 20,000 components, and more than 80 companies are involved in developing and producing a single model (Alford et al. 2000). Therefore, complicated interactions and relationships between large numbers of participants should be managed in the supply chain of the automotive industry (Bullinger et al. 1997). As illustrated in Fig. 1, the supply chain structure for the automotive industry consists of customers, an assembler, megasuppliers, first-tier suppliers, and second-tier suppliers. An assembler assembles the modules and individual assemblies into a complete product. Enterprises such as Toyota, GM, Ford, and Hyundai are automobile manufacturers. Megasuppliers, referred to as "0.5-tier suppliers," make major modules (or systems) including front-end modules, chassis corner modules, cockpit modules, and seat modules, and supply them to the assemblers. Robert Bosch GmbH, Delphi Corporation, and Hyundai Mobis are representative module manufacturers. First-tier suppliers produce individual assemblies and distribute them to the assemblers and

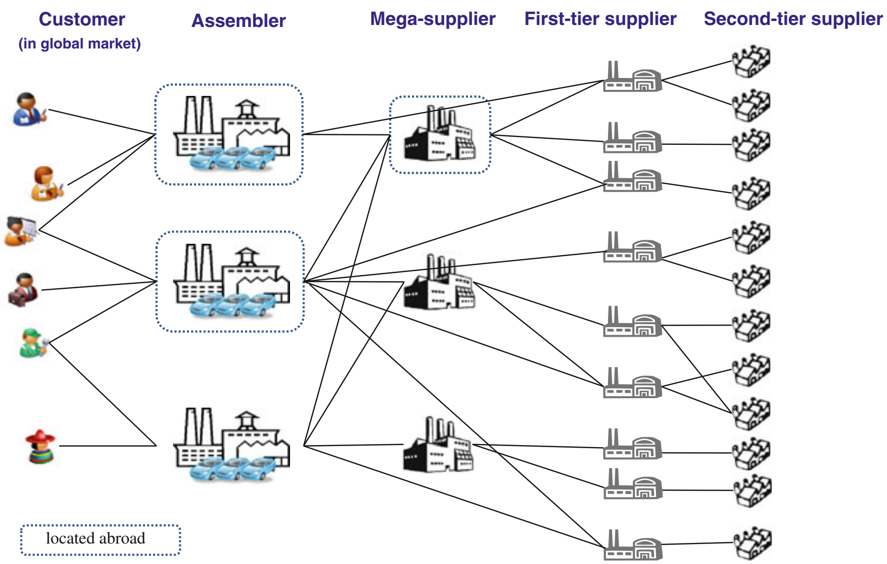

Fig. 1 Composition of the general supply chain in the automotive industry

megasuppliers. Second-tier suppliers provide parts to first-tier suppliers. The collective name for a module, an assembly, and a part is a component in this paper.

In the automotive industry, more than half the procurement of components is accomplished through outsourcing; therefore, the competitiveness of an automobile is determined by the quality of the assemblies and/or modules as well as the production technologies. As a consequence, the prices of components have a decisive influence on the price of the automobile. Therefore, to increase the profitability in the supply chain of the automotive industry, collaboration among the participants is essential. The objective of a collaborative supply chain is to gain competitive initiatives by improving the overall performance through a holistic perspective of the supply chain. Many models for collaborative supply chain management (SCM) have been developed, and these systems provide integrated planning and scheduling plans to the automobile manufacturer, module manufacturers, and assembly manufacturers (Iskandar et al. 2001; Boersma and Kingma 2005; Koh et al. 2009). In most models, however, the integrated production and procurement plans related to parts manufacturers and assembly manufacturers are not considered, because of bullwhip effects and unidentified risks (Childerhouse et al. 2008; Sucky 2009).

To manage collaboration in the supply chain for automotive industry efficiently, many strategic collaborative practices have been proposed, such as just-in-time (JIT) (Aigbedo 2007; Sandanayake et al. 2008), original equipment manufacturing (OEM) (Schilli and Dai 2006), and outsourcing (Reeves Jr et al. 2010; Moon et al. 2008). Trust of participants is one of the most important factors for implementing these strategies and managing collaborative supply chains in the automotive industry. Collaboration with trustworthy participants has a positive effect on the entire supply chain; in contrast, untrustworthy participants have a negative effect.

Furthermore, changes in the relationships between suppliers and assemblers, and the increasing global reach of the assemblers, emphasize the importance of trust in supply chain management. There is a shift towards the supply of complete functions (modules or systems) rather than individual components. Many first-tier suppliers have become megasuppliers, responsible for the assembly of parts into modules. In the past, an assembler might design a seat, make detailed drawings of 20–30 separate elements, find suppliers for each, take in the parts, and assemble them into seats in-house. Now, the assembler looks for firms (megasuppliers) that will design and supply the whole seat, or a seating system. This has become part of the process of increasing outsourcing to suppliers. Most assemblers and megasuppliers have global coverage, in order to follow their customers to various locations around the world.

Many recent studies have shown that mutual trust can contribute to knowledge sharing, resource sharing, joint risk-taking, and collaboration in SCM (Lavravc et al. 2007). However, it remains unclear how to incorporate the trust concept in SCM and optimization from an operational perspective. To deal with the trust issue related to collaboration and reduce computational load and time in production planning, this paper applies the concept of a fractal to model supply chains in the automotive industry.

The objectives of this paper are to propose a framework for collaborative fractal-based supply chain management (*c-f*SCM) in order to incorporate the trust concept in SCM, and to analyze the effects of trust values on production planning of the supply chain for automotive industry. The adaptation of the fractal concept makes it easy to capture each participant in *c-f*SCM and the interactions between participants via a self-similar structure referred to as a fractal. According to this concept, the interactions between participants can be considered and modeled as a fractal from the bottommost interactions (i.e., between assembly manufacturers and parts manufacturers) to the topmost interactions (i.e., between the automobile manufacturer and module manufacturers). A goal model of fractals is developed from an operational perspective to consider the trust value of participants during optimization processes in production planning. A trust evaluation model as well as a profit model is embodied in the goal model of a fractal. We adopt a fuzzy trust evaluation model to evaluate the trust value in numerical terms. Through the integration of each fractal's optimized goal, the production plans of an entire supply chain are optimized automatically. A simulation is conducted to analyze the effect of production plans considering the trust values of participants on the performance of the supply chain.

The remainder of the paper is organized as follows. Section 2 surveys the related literature including collaborative SCM. Literature on the fractal and the trust concept is also described. Section 3 provides a framework for *c-f*SCM and a conceptual goal model of fractals. The goal model of a fractal including trust and profit models is specified with mathematical models in Sect. 4. Finally, in Sect. 5 simulation with a numerical example of the automotive industry is presented to validate the proposed framework. Section 6 closes the paper with concluding remarks.

2 Related works

2.1 Collaborative supply chain management

Angerhofer and Angelides (2006) modeled six constituents (including stakeholders, topology, enabling technology, levels of collaboration, business strategy, and processes) of a collaborative supply chain, and described the impact of the constituents on some variables such as cost, customer demand, product quality, profit, sales quantity, time to market, forecast accuracy, and customer satisfaction with SCM. They categorized collaboration into three levels: operational, managerial, and strategic. Our research is related to the operational and managerial levels, which involve decisions for production and procurement planning. In many studies, various approaches have been applied to SCM to deal with collaborative planning problems. Selim et al. (2008) developed a multiobjective linear programming model to solve the collaborative production–distribution planning problem, and applied various fuzzy goal programming methods according to various supply chain structures. In their research, three customers, five retailers, three distribution centers, and ten plants were assumed in the supply chain. However, because they assumed a small number of participants in the supply chain, their model is not suitable for the automotive industry. Jiao et al. (2006) developed an agent-based collaborative multicontract negotiation system to support multiechelon negotiations within a dynamic supply chain. They used the negotiation technique to select capable suppliers quickly, who then sign the contract to meet the material requirements of the manufacturer, and applied the developed system to the supply chain of the mobile phone manufacturing industry. Even though their system is very useful for supporting the selection of proper suppliers, it cannot support the optimization of procurement plans. Integration of collaborative planning and supply chain optimization methodologies for the chemical process industry has also been developed by Berning et al. (2004). In their research, a genetic algorithm (GA) was used to optimize collaborative planning. However, their methodology is not appropriate for the automotive industry, because it focused on a batch process in the chemical industry. In the automotive industry, important parts and modules are considered separately, not a batch process. Ito and Salleh (2000) proposed blackboard-based negotiation to implement a collaborative supply chain system to achieve efficient material flow and shorten the production lead time. Their approach was based on the electronic negotiation method, and this method is suitable for supply chains with a small number of participants. However, it is difficult to reach agreement for a larger number of participants.

Regarding the supply chain in the automotive industry, Pierreval et al. (2007) developed a continuous simulation method. In their research, product flow through logistics units managed in a just-in-time (JIT) system and the effects of variations in demand were studied from a global perspective of performance. However, their research focused on logistics and did not consider production planning. They assumed predefined production plans but did not explain how to define these. Demeter et al. (2006) examined how the strategy of focal companies determines the configuration of the collaborative supply chain and the management practices used between supply chain participants. Their analysis was based on 17 interviews within two supply chains from the Hungarian automotive industry, where supply chains are defined according to the assemblers, where Audi and Suzuki are the focal companies. Their research was based on the interview results but did not provide mathematical models to support collaboration or to obtain detailed production and procurement plans. In many other studies, simulation or heuristic methods have been used in the automotive industry, because optimization of production planning through the entire supply chain is constrained by computational load and time (Gnoni et al. 2003; Laosirhongthong and Dangayach 2005; Qu and Williams 2008).

2.2 Fractals and their applications

The term "fractal" was coined to describe complex organisms and structures in nature that exhibit self-similar characteristics. A fractal can represent both an entire organization at the highest level and an elementary unit at the bottom level. Warnecke (1993) defined a fractal as "an independently acting corporate entity whose goal and performance can be precisely described." Ryu et al. (2003) adopted the formal definition of the fractal to solve general problems in SCM, which is referred to as fractal-based supply chain management (*f*SCM). They modeled a basic fractal unit, which consists of five functional modules including an observer, an analyzer, a resolver, an organizer, and a reporter, by using unified modeling language (UML). Five functional modules conduct the assigned jobs to achieve their goals through negotiations and cooperation between each other (Ryu and Jung 2003). The observer monitors the state of the unit and receives messages from the outer fractals, and transmits composite information to the corresponding fractals. The analyzer performs profitability analysis of the fractal using status and cost information. The resolver performs the goal-formation and decision-making processes. The organizer manages the fractal status and fractal addresses for dynamic restructuring processes. The reporter conveys the results from all the processes within the fractal to other fractals. Refer to Ryu et al. (2003) for more information on the functions of the modules. The analyzer and the resolver play more important roles than the other modules, because they perform operations that are required for making decisions in *f*SCM. Ryu et al. (2003) applied the fractal concept to SCM for an e-business company (in particular, a B2C company) and specified the analyzers and resolvers for each individual fractal using mathematical models.

In *f*SCM, to represent supply chain members, a fractal echelon (a group of members with multi- or heterofunctional fractals) was used. Each member in the supply chain becomes a fractal, and any combination of members can be another fractal. In *f*SCM, transactions and collaboration between supply chain members are based on the cost factors of participants. In *f*SCM, a customized numerical model for the analyzer and resolver in an e-biz company has been developed. In the numerical model for the analyzer, the profit of a fractal is analyzed. In the resolver, the objective function and constraints for maximization of profit are generated and solved. In the objective function, the factors including transportation cost, refund or A/S cost, customers' price, purchasing cost, and advertisement cost are considered to maximize profit. The resolver's numerical model includes constraints related to customers' demand, refund or A/S capacity, and manufacturer production capacity.

The proposed *c*-*f*SCM framework operates under the fractal architecture including the five functional modules of *f*SCM. A fractal echelon is also used to represent the supply chain members and relationships for *c*-*f*SCM. In *c*-*f*SCM, transactions and collaboration are based on the trust of participants as well as cost factors. The concept of the goal formation and goal optimization procedures in *c*-*f*SCM are based on those in *f*SCM. The goal of the numerical model for the analyzer is also maximization of profit in the proposed framework. Because the detailed numerical models are developed for an automotive industry in *c*-*f*SCM, however, there are some differences between the detailed numerical model of *f*SCM and *c*-*f*SCM. The comparison of *c*-*f*SCM and *f*SCM is summarized in Table 1.

Table 1 Comparison of *c*-*f*SCM and *f*SCM

	c-*f*SCM	*f*SCM
Representation of SC members	Fractal echelon	Fractal echelon
Nature of collaboration	Trust- and cost-based collaboration	Cost-based collaboration
Application domain	Automotive industry	e-biz company

The application domain has a great impact on the detailed numerical models in *c-f*SCM and *f*SCM. Because the main concern of a company in an e-biz environment is the local transaction with final customers, the globalization concept is not important. In automotive industry, however, international transactions with wholesalers or suppliers are very important. In the numerical models of *c-f*SCM, heterogeneous participants and transportation costs according to geometrical location are assumed. Multiple customers and manufacturing plants with different geometrical location are also assumed in *c-f*SCM, while one customer and one e-biz company is assumed in *f*SCM, Furthermore, supply chain members are categorized into two groups according to their globalization. A characteristic of an e-biz company is that it normally does not produce but purchases final products and delivers them to customers such as a shopping agent. Therefore, while production capacity and inventory cost are significantly considered for optimization of the numerical model in *c-f*SCM, they are not considered in *f*SCM.

The numerical model of *f*SCM is not recursive. Because the model was specified for the relationships between a final customer and a huge retailer (the top-level hierarchy), some specific cost factors and constraints including advertisement cost, refund and A/S cost, and capacity are considered. To apply the model to another level of hierarchy (for example, relationships between first-tier suppliers and second-tier suppliers), the objective function and constraints should be redefined. A more generalized objective function and simplified constraints are assumed in *c-f*SCM to use the model recursively at all levels of the hierarchy. This generalized model has the advantage of coping with change of the supply chain hierarchy; For example, if one more level of hierarchy is added to the supply chain structure, *c-f*SCM model could reflect this change by just adding fractals representing the new relationships and using the fractal's numerical model without any modifications.

2.3 Trust

Trust is an abstract concept used in many kinds of interactions, allowing people or organizations to act under uncertainty with the risk of negative consequences (Fukuyama 1995). McCutcheon and Stuart (2000) defined trust as "the belief that the other party will act in the firm's best interest in circumstances where that other party could take advantage or act opportunistically to gain at the firm's expense." In another study, trust was defined as the willingness of the truster to be vulnerable to the actions of another party based on the expectation that the trusted party will perform a particular action important to the truster, irrespective of the ability to monitor or control the trusted party (Lane and Bachmann 1999). Currall and Inkpen (2002) indicated that trust is the decision to rely on a partner with the expectation that the partner will act according to a common agreement. Trust has been studied widely in the literature on virtual organizations or enterprises (Fukuyama 1995; Lavravc et al. 2007; Msanjila and Afsarmanesh 2008). Mun et al. (2009a, b) applied the trust concept to create a virtual organization. In their research, a goal-oriented trust model and a fuzzy trust evaluation model were proposed. The evaluation model is generated through two phases, including factor selection and the design of a fuzzy inference system. In the factor selection phase, the trustor selects the factors related to the predefined goal. Fuzzy sets, membership functions, and fuzzy rules are designed in the design phase of the fuzzy inference system.

In some of the literature on supply chains, the impact and role of trust have been examined in terms of collaboration at the strategic level (Akkermans et al. 2004; Handfield and Bechtel 2003; Panayides and Lun 2009). However, few studies consider trust at the operational or managerial levels. Kwon and Suh (2006) investigated the relationship between trust and commitment using empirical testing. Moore (2006) examined the role of trust in logistics alliances, and empirically tested it by using a sample of logistics alliances.

3 A framework for collaborative fractal-based supply chain management (*c-f*SCM)

There are several advantages of *f*SCM for solving problems in SCM, and they are valid in our framework as well, i.e., *c-f*SCM for the automotive industry. Firstly, it becomes easy to understand and manage a complex system. The supply chain for the automotive industry has very complex and massive interactions. These interactions can be easily managed, because similar functional modules are iteratively applied at various fractal levels. In a centralized master planning model, if some participants are added to the system, a master objective function and all constraints should be remodeled. However, in *c-f*SCM, this problem can be controlled by adding new fractals representing the new participants, only developing a goal model of the new fractals. Therefore, in static collaboration situations, the proposed model cannot show advantages in comparison with the centralized master planning method. However, in dynamic collaboration situations where the formation and information of participants are frequently changing, the proposed model could be more suitable than the centralized master planning method. Secondly, local optimization distributes the computational load and time. In *c-f*SCM for the automotive industry, a large-sized problem for production and procurement planning can be decomposed into smaller ones so that problems can be solved more easily and faster. Finally, flexible management of supply chains is possible. The fractal-based numerical model can integrate existing supply chain models; for example, assuming that a goal model in the past was to minimize the production cost of module manufacturers in the supply chain, if we now want to include the costs of assembly manufacturers in the goal model, we can easily modify or extend the model by integrating the separate cost models of assembly manufactures into the earlier model after developing a new goal model for the assembly manufacturers. While doing this, the consistency of goals can be maintained according to the inherent characteristics of the fractal architecture. For a similar reason, a trust model also can be easily integrated into a profit or goal model.

The proposed *c-f*SCM framework is developed for the automotive industry. Therefore, features of the automotive industry should be considered in the supply chain management model during the production planning.

- Globalization should be reflected in the model. In the automotive industry, customers are distributed to various locations around the world, and an

assembler can have assembly plants abroad as well as in its own country. In addition, the number of international megasuppliers and first-tier suppliers is increasing. This means that firms in the supply chain should be classified into global and local firms, and their transportation cost and delivering time should also be classified into global and local costs.
- Outsourcing should be reflected in the model. Modularization of assemblies and parts has accelerated further. This reveals that the outsourcing ratio of assembling operations is increasing. In the production planning phase, the model should be able to determine which modules or parts should be outsourced and the outsourcing ratio according to costs and delivery time.
- Trust of participants should be considered during the production planning. As mentioned in Sect. 1, because globalization and modularization emphasize the importance of trust, trust of participants should be represented in numerical terms.
- The model should be able to provide an easy way to understand and represent a complicated supply chain structure.
- Because customer demand, which is used in the production planning phase, includes expected customer demands and actual precontract orders, and the ratio of precontract orders in the automotive industry is higher than in other industries, unfulfilled precontract orders for cost savings should not be permitted.

The detailed numerical models concerning the above features are described in Sect. 4.

3.1 Composition of fractals

In *f*SCM for an e-business, each member of the supply chain becomes a fractal. However, in the framework proposed in this paper, each interaction between participants in the supply chain becomes a fractal. In other words, buyer–seller relationships are represented as a fractal. A fractal is composed of participants and subfractals. Participants who act as sellers belong to the fractal, and participants who act as buyers belong to the subfractals.

To define fractal structure, we remodel a supply chain of the automotive industry based on the manufacturing capability for a complete product or components. Figure 2 illustrates the remodeled supply chain structure of Fig. 1. The supply chain structure includes complete product manufacturers (including assembling plants), module manufacturers (including assembling plants and megasuppliers), assembly manufacturers (including first-tier supplier), and parts manufacturers (including second-tier supplier). Basically, the fractal composition is defined according to the types of modules. Figure 3 illustrates the composition of fractals. In Fig. 3, *Fractal_automotive* represents the entire supply chain in the automotive industry. According to the type of modules, the supply chain of the automotive industry (*Fractal_automotive*) is decomposed into several fractals including *fr*_1 through *fr*_4. Fractal *fr*_d1 represents the relationship between customers and complete product manufacturers, and deals with assemblies and module orders. Complete

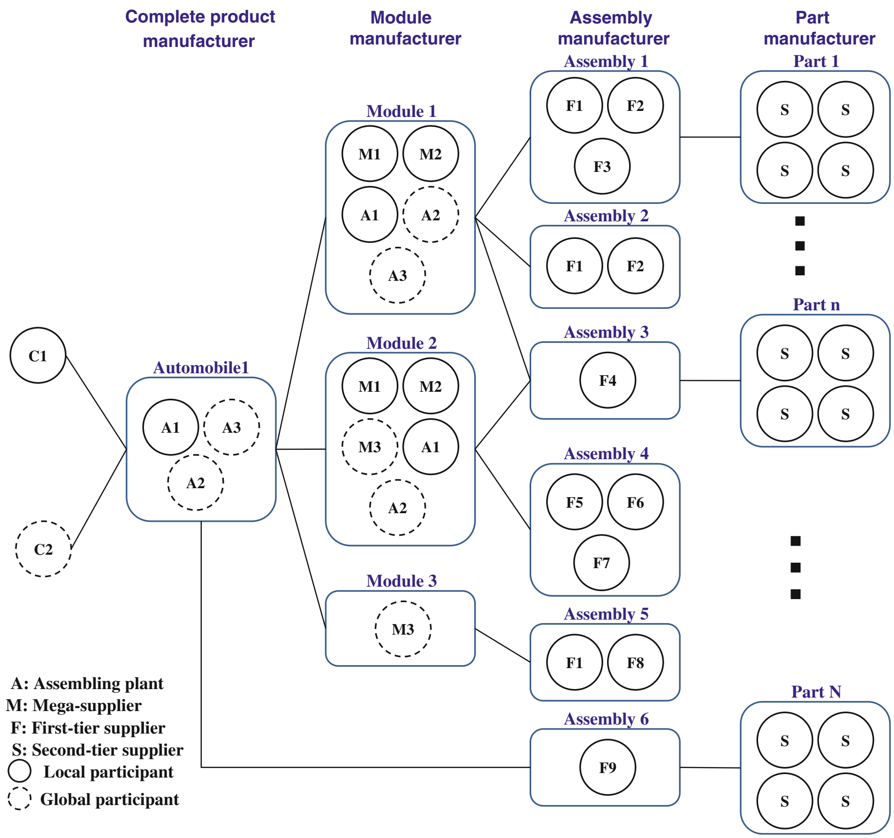

Fig. 2 Supply chain structure based on manufacturing capability

product manufacturers interact with module and assembly manufacturers to procure the modules and parts for producing an automobile. In this case, the interaction between the complete product manufacturers that act as the buyers and module manufacturers (or assembly manufacturers) that act as the sellers can be considered as a fractal (*fr*_m1 through *fr*_m4 in Fig. 3). The fractal *fr*_m1 is composed of module manufactures (M1, M2, A1, A2, A3) and a subfractal, *fr*_d1. As is the case with *fr*_m1, *fr*_a1 is composed of assembly manufacturers (F1 through F4) and a subfractal, *fr*_m1.

The supply chain is decomposed into fractals to distribute the computational load and time during optimization of production planning. Assume that the supply chain has ten module manufacturers, each of which has five assembly manufacturers who are supported by five parts manufacturers. To optimize production planning for the entire supply chain through a mixed integer programming approach, an optimization system should simultaneously consider 250 integer variables. In the proposed framework, the supply chain is decomposed into ten fractals according to the types of module; each fractal optimizes its production planning using 25 integer variables.

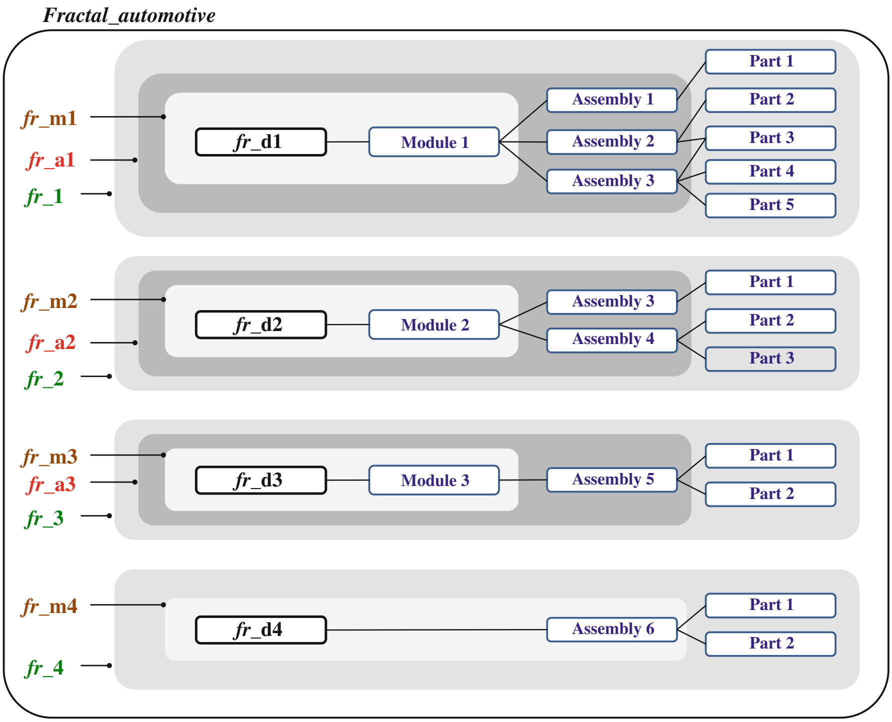

Fig. 3 Composition of fractals based on module type

3.2 Goal model of fractals

Each fractal has its own goal and acts to achieve that goal in *c-f*SCM. There are many types of goal, such as maximizing profit, minimizing cost, reducing lead time, and improving production efficiency, that can be represented in a goal model of a fractal. To achieve these goals, each fractal maximizes its goal model. Detailed numerical instances of the goal model are described in Sect. 4.

Through optimization of the goal model, production plans for each participant are optimized. The optimizations are performed iteratively from the bottom-level fractals to the top-level fractal. For the case illustrated in Fig. 3, the procedure of goal optimization is shown in Fig. 4.

Firstly, *fr*_d1 optimizes production plans for a complete product based on customer demand. According to the optimization results for *fr*_d1, *fr*_m1 through *fr*_m3 generate production plans for the modules. The production plans for assemblies are generated by *fr*_a1 through *fr*_a4 based on the module manufacturers' demands.

3.3 Trust in the goal model of fractal

In the *c-f*SCM framework, the trust value of participants refers to the degree of compliance with predefined conditions of the contract. In supply chain management,

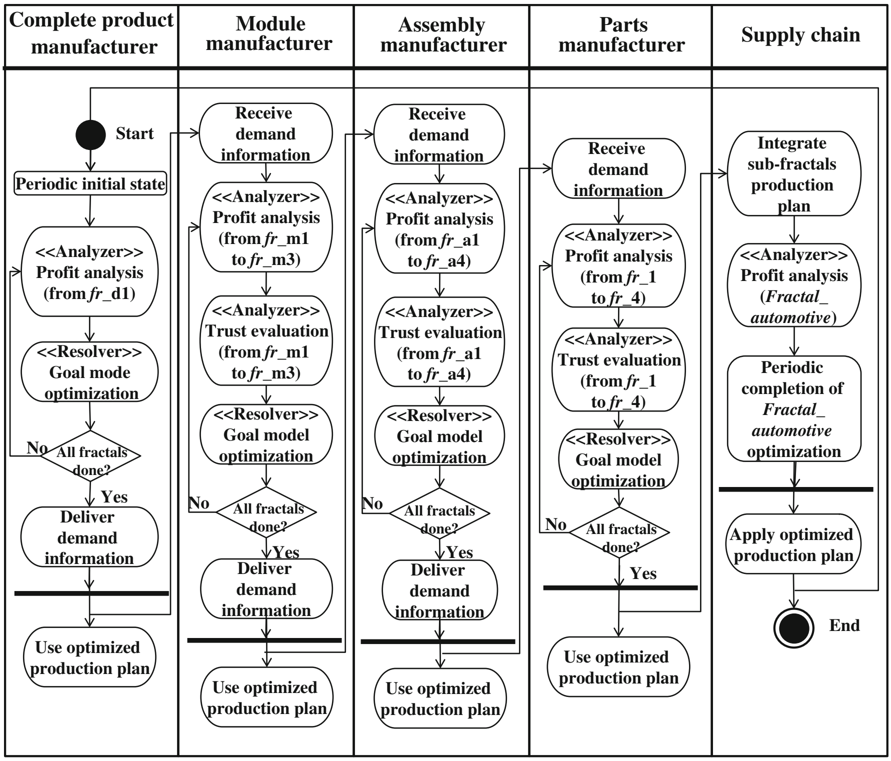

Fig. 4 Procedure for goal optimization

compliance with conditions can be represented by various factors, including conformance to specifications and conforming to the stipulated delivery date. It is important to consider these factors in supply chain management, because they influence indicators of supply chain performance such as refund cost, safety stock level, time to market, total inventory cost, and price of product. In the automotive industry, because the procurement ratio of components from partners is very high, factors related to trust should be considered to increase the profit of the entire supply chain of the automotive industry. However, it is not easy to consider these factors in the phase of production and procurement planning. If participants in a supply chain are not compliant with the optimized production plan, the performance of the entire supply chain will suffer.

In this paper, the trust value is used for optimizing the production plans of participants in the fractal in the goal model. The trust value has an effect on the production quantities for assemblies or modules and the levels of safety stock in production planning. A higher trust value of a participant induces the participant to make more products and have a lower level of safety stock during optimization of the goal model. The intended influences of the trust value are embodied in the goal model of the fractal.

In this paper, the number of defects (related to conformance to specifications) and the ratio of due dates violated (related to conformance to the due date for delivery) are used to evaluate the trust value of participants in fractals. We use fuzzy logic to gain a crisp value for trust, because it is very difficult to design a function that generates a trust value using heterogeneous input variables. The number of defects and due date violations could not be used directly in the arithmetic operation without modification. Fuzzy logic is helpful to deal with this approximate rather than accurate reasoning. Furthermore, if a decision-maker wants to add one more factor to evaluate the trust, it is very easy to reflect the change to the system by developing just one more fuzzy set related to the added factor in the fuzzy-logic-based model. The detailed method for evaluating trust is described in Sect. 4.

4 Numerical modeling of a fractal

As mentioned earlier, among the five functional modules, the analyzer and the resolver are associated with decision-making in production planning. The analyzer performs profitability analysis and trust evaluation of the fractal using status and cost information. The resolver executes the goal optimization processes. In this section, numerical models of the analyzer and the resolver are described. The analyzer has a profit model and a trust evaluation model, and the resolver has a goal model.

4.1 Profit model of a fractal

The analyzer uses a profit model to analyze the profit of the fractal. The profit model in the analyzer is based only on the cost of fractals at each level, since intangible factors (such as customers' propensity to consume, satisfaction after buying goods, etc.) are difficult to express numerically. The profit models of the top-level fractals can be built from the simple model of bottom-level fractals by adapting simple models iteratively. The profit calculations are also performed iteratively form the bottom-level fractal to the top-level fractal. To define the profit model of a fractal, the following notation is used in this paper:

$P_{fractal}$ Profit of the *fractal*
f Index of the subfractals of *fractal* ($f = 1,\ldots, F$)
i Index of participants ($i = 1,\ldots, I$)
j Index of customers ($j = 1,\ldots, J$)
k Index of suppliers ($k = 1,\ldots, K$)
l Index of products ($l = 1,\ldots, L$)
m Index of components ($m = 1,\ldots, M$)
n Index of orders

$$\begin{cases} n = 1,\ldots,v_{ijl} & \text{if orders are placed by customer } j \\ n = 1,\ldots,h_{ikm} & \text{otherwise} \end{cases}$$

v_{ijl} Total number of orders placed by customer j for participant i regarding product l

h_{ikm} Total number of orders placed by participant i for supplier k regarding component m

v_{ijln} Order quantity of nth order placed by customer j for participant i regarding product l

h_{ikmn} Order quantity of nth order placed by participant i for supplier k regarding component m

P_{ijl} Customer price of j for product l from participant i

c_{ikm} Unit purchasing cost of component m made by supplier k in participant i

As_{il} Fixed cost for processing one unit of product l in participant i

A_{ikm} Fixed ordering cost for an order placed by participant i for supplier k about component m

Hs_{il} Inventory cost of product l made in participant i

H_{im} Inventory cost of component m in participant i

t_{ijl} Transportation cost of one order placed by customer j for participant i regarding product l

r_{ijl} Back-order cost of participant i for customer j regarding product l

The profit model of a fractal is as follows:

$$P_{fractal} = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{l=1}^{L}\left[\sum_{n=1}^{v_{ijl}}\left\{v_{ijln} \times \left(p_{ijl} - As_{il} - \frac{1}{2}Hs_{il}\right) - t_{ijl}\right\} - r_{ijl}\right] - \sum_{i=1}^{I}\sum_{k=1}^{K}\sum_{m=1}^{M}\sum_{n=1}^{h_{ikm}}\left\{h_{ikmn} \times \left(c_{ikm} + \frac{1}{2}H_{im}\right) + A_{ikm}\right\} + \sum_{f=1}^{F} P_f. \quad (1)$$

In Eq. 1, the sales profit, production, inventory, and transportation costs for products, refund, purchasing, and inventory costs for components and the ordering cost are considered. Without modifying the model, the proposed profit model can be used at all levels of the fractal in the fractal-based collaborative supply chain management. Of course, the set of subfractals, participants, customers, suppliers, products, and components vary depending on the level of the fractal. In the case of *fr*_a1 in Fig. 3, F1 through F4 are participants, M1, M2, A1, A2, and A3 are customers, and *fr*_m1 is a subfractal. In the automotive industry, module manufacturers can purchase several kinds and multiple quantities of assemblies from one assembly manufacturer at a time. Therefore, one order can contain one or more assemblies or parts. The total profit of the entire supply chain can be calculated by the summation of all the subfractals in the supply chain. The result of profit analysis will be used to optimize the goal of each fractal by the resolver.

4.2 Trust evaluation model of a fractal

In the *c*-*f*SCM framework, the trust value of a participant refers to the reliability of the quality of components made in the participant and the conformance to stipulated due dates. A fractal uses a trust evaluation model to analyze the trust of the participants that belong to the fractal. The ratio of defects is used to analyze the reliability of quality, and the average due date violation is used to analyze the conformance to stipulated due dates. The ratio of defects affects the total cost of the supply chain and manufacturing or assembling schedule. Due date violation is related to the total lead time of the final product and directly affects the customer service level. The ratio of defects and due date violations are objective data which could be easily gathered using past trading data. In the paper, due date violation refers to the elapsed time from the due date.

Here the fuzzy inference system, proposed by Mun et al. (2009a), is applied to develop the trust evaluation model. The fuzzy inference system is composed of input and output variables, fuzzy sets, fuzzy rules, and defuzzification schemes, as illustrated in Fig. 5. In *c-f*SCM, two input variables and one output variable are used to evaluate the trust values. The input variable v_1 is the ratio of defects and v_2 is the average due date violation. The values of the input variables can be determined according to past information about the fractal. *Trust* is the output variable. As illustrated in Fig. 6a, b, the values of input variables are fuzzified according to the fuzzy sets. The fuzzy rules can be simply designed as summarized in Table 2. According to the fuzzy rules, *Trust* is fuzzified. The defuzzification scheme is used to obtain the defuzzified, crisp value according to the output variable. In this paper, we used the centroid-of-area method as the defuzzification scheme to obtain the trust value of each participant, which is the most widely used method. The evaluated trust value is in the range of 0 to 1. If a participant is completely reliable, the evaluated trust value of that participant will be 1.

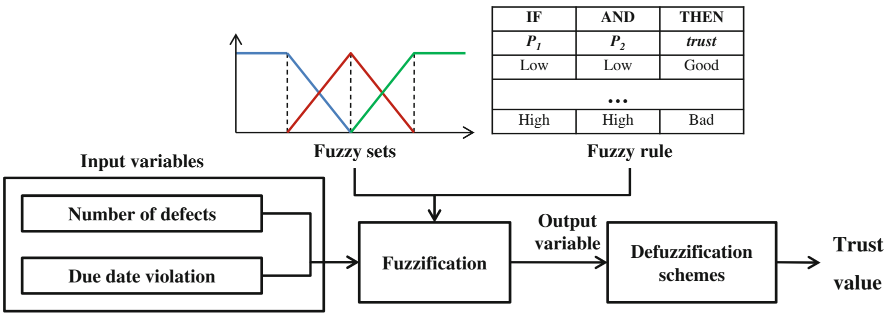

Fig. 5 Fuzzy inference system for trust evaluation in the automotive industry

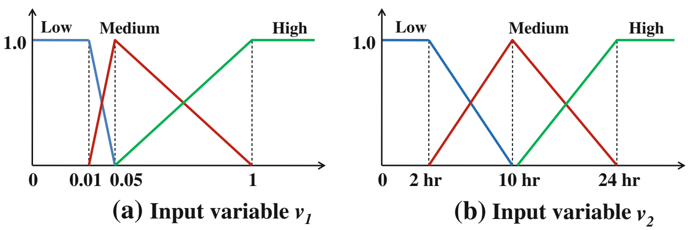

Fig. 6 Fuzzy sets for the input variables

Table 2 Fuzzy rules

IF v_1	AND v_2	THEN *Trust*
Low	Low	*Good*
Low	Medium	*Good*
Low	High	*Normal*
Medium	Low	*Good*
Medium	Medium	*Normal*
Medium	High	*Bad*
High	Low	*Normal*
High	Medium	*Bad*
High	High	*Bad*

The evaluated trust value of participants is integrated into the goal model of the fractal to optimize the production plan of participants of the fractal. The trust value has an effect on the production quantities for assemblies or modules and the level of safety stock in production planning.

4.3 Goal model of a fractal

The resolver generates the production plan through optimization of the goal model. In the goal model of a fractal, the subfractals' optimized production plans are used as the demands of customers. Procurement planning of assemblies or parts is not considered in the optimization of the goal model, because it will be optimized in the upper-level fractal's goal model. Because a fractal has the characteristic of self-similarity, the goal model of the fractal has the same form at all levels of the fractal. In the case of *fr*_a1 in Fig. 3, F1 through F4 are participants, and M1, M2, A2, A2, and A3 are customers. In the special case where the fractal is the top-level fractal (*Fractal_automotive* in Fig. 3), the fractal integrates the optimized production plans of the subfractals. Because the top-level fractal has no participants, however, it does not optimize its goal model. To define the goal model of a fractal, the following notation is used in this paper:

g_f Goal model of the fractal f
i Index of participants in fractal f ($i = 1,\ldots, N$)
j Index of customers ($j = 1,\ldots, M$)
k Index of products ($k = 1,\ldots, K$)
$trust_{ik}$ Trust value of participant i for product k
v_{jk} Unit price of product k for customer j
As_{ik} Unit processing cost for product k by participant i
t_{ijk} Unit transportation cost for product k from participant i to customer j
dt_{ijk} Unit delivery time for product k from participant i to customer j
pt_{ik} Unit processing time for product k by participant i
Hs_{ik} Unit inventory cost for product k in participant i
d_{jk} Demand of customer j for product k
c_{ik} Capacity of participant i for product k

c_i Total capacity of participant i
cl_j Index of locations for customer j
pl_i Index of locations for participant i
gl_i Globalization index of participant i

$$\begin{cases} gl_i = 0 & \text{if participant } i \text{ is a global company} \\ gl_i = 1 & \text{otherwise} \end{cases}$$

The following decision variables are used in the model:
x_{ijk} = quantity of product k made in participant i for customer j
If the goal of a fractal is the maximization of profit, the goal model of the fractal is as follows:

$$\begin{aligned} \max g_f = &\sum_{j=1}^{M}\sum_{k=1}^{K} v_{jk}d_{jk} - \sum_{i=1}^{N}\sum_{k=1}^{K}\left\{\left(1+\frac{\alpha}{trust_{ik}}\right)\times As_{ik}\times\left(\sum_{j=1}^{M}x_{ijk}\right)\right\} \\ &-\sum_{i=1}^{N}\sum_{k=1}^{K}\left\{\left(1+\frac{\alpha}{trust_{ik}}\right)\times\frac{1}{2}Hs_{ik}\times\left(\sum_{j=1}^{M}x_{ijk}\right)\right\} \\ &-\sum_{i=1}^{N}\sum_{k=1}^{K}\left\{\left(1+\frac{\alpha}{trust_{ik}}\right)\times\left(\sum_{j=1}^{M}t_{ijk}x_{ijk}\right)\right\} \end{aligned} \tag{2}$$

$$\text{subject to} \quad \sum_{i=1}^{N} x_{ijk} \geq d_{jk} \text{ for } \forall k \text{ and } \forall j \tag{3}$$

$$\sum_{i=1}^{N} x_{ijk} \times \frac{1}{\{1+(1-trust_{ik})\times\beta\}} \geq d_{jk} \text{ for } \forall k \text{ and } \forall j \tag{4}$$

$$\sum_{j=1}^{M} x_{ijk} \leq c_{ik} \quad \text{for } \forall i \text{ and } \forall k \tag{5}$$

$$\sum_{j=1}^{M}\sum_{k=1}^{K} x_{ijk} \leq c_i \quad \text{for } \forall i \tag{6}$$

$$(cl_j - pl_i)\times gl_i \times x_{ijk} = 0 \quad \text{for } \forall i,\ \forall j \text{ and } \forall k \tag{7}$$

$$x_{ijk} \geq 0 \quad \text{for } \forall i,\ \forall j \text{ and } \forall k \tag{8}$$

Equation 2 is the objective function of the goal model. The main objective of a goal model in the proposed framework is to maximize the expected total profit of the fractal. The sales profit, production, inventory, and transportation costs for products are considered in the proposed objective function. The objective function is designed to assign cost penalties to the participants according to their trust values. A higher value of $trust_{ik}$ can induce the fractal to judge participant i to be the more cost-efficient partner, and to assign a greater production quantity for product k to participant i. In the objective function, α is the coefficient for the cost penalty. In the case where α is 0, the model will not consider the cost penalty, which is determined according to the trust value, during the optimization procedure. Equation 3 implies that the quantity of products made in participants should be larger than the demand of customers. In Eq. 4, the level of safety stock is determined according to the trust value of participants, and β is the coefficient of safety stock. A lower trust value for a participant induces the participant to have a higher level of safety stock. Since a lower trust value for a participant means that the participant has higher probability of making defective products or violating due dates, that participant should hold more safety stock. If β is 0, the model will not consider the safety stock during production planning, and Eq. 4 is the same as Eq. 3. Since the values of α and β have a great effect on production planning, the effectiveness of α and β should be examined before using the proposed approach in real-world cases. Equations 5 and 6 are the constraints for the production capacity. Equation 7 is the transaction constraint, reflecting that a local participant cannot supply a product to a customer with a different location index. Equation 8 is a constraint for positive value of x_{ijk}.

If the goal of a fractal is minimization of lead time, the goal model of the fractal can be represented as in Eq. 9.

$$\min g_f = Max\{sign(x_{ijk}) \times dt_{ijk} + sign(x_{ijk}) \times pt_{ik}\} \tag{9}$$

Equations 3 though 8 are also used as the constraints in this goal model.

5 Simulation

Simulations were conducted to validate the operability of the *c-f*SCM framework in the automotive industry and to examine the effect of the trust value on supply chain performance. We applied the proposed framework to an illustrative supply chain and used various values of α and β in Eqs. 2 and 3, various demand patterns, and various cost configurations (transportation cost) as input parameters for the simulations. The results of the simulation are compared according to the total profit of the supply chain.

5.1 Illustrative supply chain of the automotive industry

The example assumes a supply chain that consists of 3 final customers (C1 through C3), 3 assembling plants (A1 through A3), 10 megasuppliers (M1 through M10), 20 first-tier suppliers (F1 through F20), and 40 second-tier suppliers (S1 through S40). We assumed that global firms could supply their products to participants located in different countries. We also assumed 1 type (automobile_1) of complete product, 5 types (module_1 through module_5) of modules, 20 types (assembly_1 through assembly_20) of assemblies, and 20 types (part_1 through part_20) of parts. The assembling plants buy or produce the modules, and assemble them into a complete product. Basic information for the participants related to module_1 is summarized in Table 3. Participants related to module_2 through module_5 have the same information pattern as shown in Table 3. The assembly manufacturers are usually supported by local suppliers (parts manufacturers) to maintain cost efficiency, although the automotive industry is starting to be increasingly globalized. Thus, in the example, we assumed that each assembly

Table 3 Basic information on the participants related to module_1

Participant	Product	Processing cost ($/unit)	Capacity (units/month)	Error rate (%)	Location
A1 (Global)	Automobile	7,000	400	5	Country_1
	module_1	400	400	10	
A2 (Global)	Automobile	5,000	400	10	Country_1
	module_1	200	400	15	
A3 (Global)	Automobile	4,000	400	20	Country_2
	module_1	150	400	25	
M1 (Global)	Module_1	300	1,000	1	Country_4
M2 (Global)	Module_1	200	1,000	5	Country_1
F1 (Global)	Assembly_1 through assembly_4	20	2,400	5	Country_4
F2 (Global)	Assembly_1 through assembly_4	16	2,400	7	Country_1
F3 (Local)	Assembly_1 through assembly_4	12	2,400	15	Country_1
F4 (Local)	Assembly_1 through assembly_4	10	2,400	25	Country_2
S1 (S3, S5, S7)	Part_1 through part_4	6	10,000	10	
S2 (S4, S6, S8)	Part_1 through part_4	5	10,000	20	
C1	None	None	None	None	Country_1
C2	None	None	None	None	Country_2
C3	None	None	None	None	Country_3

manufacturer has two local parts manufacturers. The error rate refers to the probability that the participants made a defective product.

As shown in Table 3, the participants with lower error rates show higher processing costs. Therefore, the question is which one among the cost-efficient partner and trustworthy partner is an appropriate choice. Another question is the modularization. Module_1 could be outsourced to M1 and M2, and could be also assembled in-house in A1 through A3.

To produce one unit of automobile_1, one unit of each type of module is needed. Two units of assembly_1 through assembly_4 are used to produce one unit of module_1, and two units of part_1 through part_4 are used to produce one unit of assembly_1. Detailed information about the components is summarized in Table 4.

Regardless of the type, the unit transportation costs of automobile, modules, assemblies, and parts are $150/unit, $30/unit, $4/unit, and $1/unit, respectively, in the same country. The unit transportation cost of global logistics is twice that of domestic logistics. In the case of in-house assembling for a module, the transportation cost is 0. The inventory cost of automobile, modules, assemblies, and parts are $200/unit, $50/unit, $10 and $1/unit, respectively. The back-order cost is the same as the product price.

5.2 Simulation setup

For the simulation, first, the structure of the illustrative supply chain was converted to a fractal structure. The detailed composition of the fractals is summarized in

Table 4 Relationships between components

Product	Necessary components for production	Price ($/unit)
Automobile_1	1 unit of module_1 through module_5	20,000
Module_1	2 units of assembly_1 through assembly_4	2,000
Module_2	2 units of assembly_6 through assembly_9	2,000
Module_3	2 units of assembly_9 through assembly_12	2,000
Module_4	2 units of assembly_13 through assembly_16	2,000
Module_5	2 units of assembly_17 through assembly_20	2,000
Assembly_1 through assembly_4	2 units of part_1 through part_4	150
Assembly_5 through assembly_8	2 units of part_5 through part_8	150
Assembly_9 through assembly_12	2 units of part_9 through part_12	150
Assembly_13 through assembly_16	2 units of part_13 through part_16	150
Assembly_17 through assembly_20	2 units of part_17 through part_20	150
Part_1 through part_20	None	10

Table 5 Fractal composition in the example

Fractal	Subfractal	Participant	Fractal	Subfractal	Participant
fr_auto	*fr*_1 to *fr*_5	None	*fr*_a3	*fr*_m3	F9 through F12
*fr*_1	*fr*_a1	S1 through S8	*fr*_a4	*fr*_m4	F12 through F16
*fr*_2	*fr*_a2	S9 through S16	*fr*_a5	*fr*_m5	F17 through F20
*fr*_3	*fr*_a3	S17 through S24	*fr*_m1	*fr*_d1	M1, M2, A1, A2, A3
*fr*_4	*fr*_a4	S25 through S32	*fr*_m2	*fr*_d2	M3, M4, A1, A2, A3
*fr*_5	*fr*_a5	S33 through S40	*fr*_m3	*fr*_d3	M5, M6, A1, A2, A3
*fr*_a1	*fr*_m1	F1 through F4	*fr*_m4	*fr*_d4	M7, M8, A1, A2, A3
*fr*_a2	*fr*_m2	F5 through F8	*fr*_m5	*fr*_d5	M9, M10, A1, A2, A3
			*fr*_d1 to *fr*_d5	None	A1, A2, A3, C1, C2, C3

Table 5. The trust evaluation model was designed using Xfuzzy 3.0 (IMSE-CNM), and the optimization of the goal model of each fractal in Table 5 was implemented using the commercial software What's *Best!* 10.0 by LINDO Systems Inc.

The trust value of participants is evaluated according to past data in the simulation. The initial trust value of each participant is 1. Based on the profit analysis and trust evaluation, the goal model generated the optimized production plan of each participant in the supply chain. The optimized production plan was used as input data in the simulation model, and the simulation model gave feedback data, including actual production, sales, number of defects, and lead time to the profit and trust evaluation model, as illustrated in Fig. 7. We used the commercial 3D simulation software AutoMod 12.2 by Brooks Automation Inc.

The simulation was conducted based on the following assumptions:

- The actual customer demand for the final product (an automobile) follows a normal distribution.

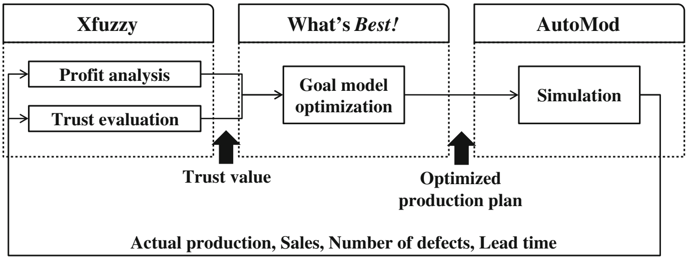

Fig. 7 The simulation procedure

- The trust value of each participant is updated monthly.
- A production plan is generated monthly.
- Participants procure components (modules, assemblies, and parts) daily in the domestic environment.
- Participants procure components weekly in global transactions.
- Each participant has an infinite inventory capacity and infinite transportation capacity.

In the simulation, customer demand (units/month) follows a normal distribution. We assumed that the transportation time (h/unit) for all types of product including automobile, module, assemblies, and parts was N(24, 2) in domestic and N(168, 24) in global transactions, where N stands for a normal distribution. The simulation was carried out for a year and replicated 10 times. In the simulation, we used 400 combinations of α and β. The values of α and β were changed from 0 to 2 with increments of 0.1. The trust values of participants were not considered during production planning when the values of the two input parameters were 0. *c*-*f*SCM was used to generate production plans if the value of α was larger than 0. The level of safety stock was determined according to Eq. 5 if the value of β was larger than 0. In other cases, the level of safety stock was 10% of the expected demand. Two independent factors, including the variability in customer demand, and difference between global and domestic transportation costs, were used in all simulation experiments. The number of levels of these factors and their values are listed in Table 6. The three customers have the same demand distribution in the simulation.

5.3 Simulation results and discussion

Figure 8 illustrates the simulation results when the level of all independent factors was 1. As illustrated in Fig. 8a, a radical change of profits is observed when the

Table 6 Independent factors of the simulation

Independent factors	Levels		
	1	2	3
Factor 1: variability in customer demand	N(300, 15)	N(300, 30)	N(300, 60)
Factor 2: transportation cost (global:domestic)	2:1	3:1	4:1

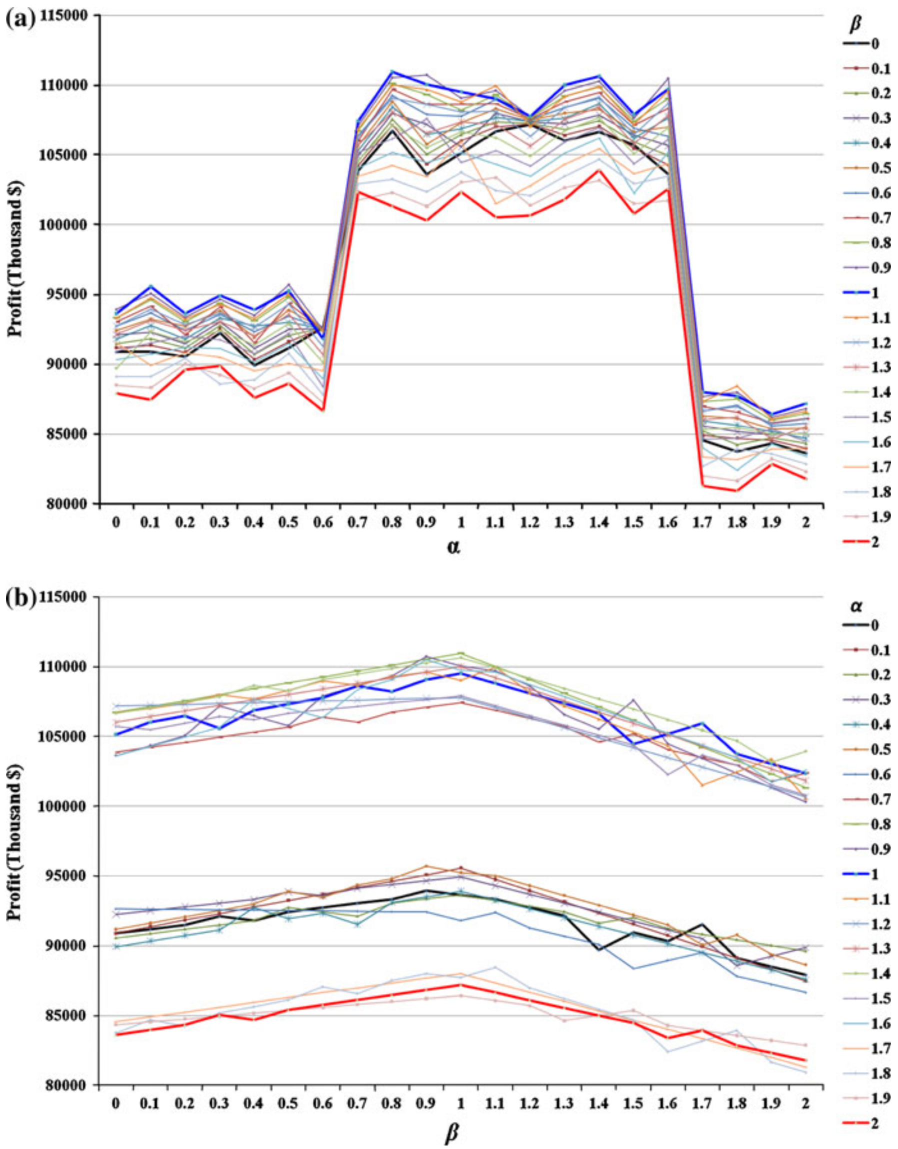

Fig. 8 Simulation results

value of α is around 1 for all values of β. Examination of Fig. 8a also reveals that the simulation shows poor performance when the value of α is around 0 and 2 for all values of β. Examination of Fig. 8b reveals that the best performance is observed when the value of β is around 1, and the worst performance when the value of β is around 2, regardless of α. At all levels of independent factors, the same results were observed. For more detailed examination of the simulation results, we selected representative simulations. Selected simulations are listed in Table 7, and their

Table 7 Simulations selected for analysis and discussion

Simulation	Input parameters		Simulation	Input parameters	
Sim_1	$\alpha = 0$	$\beta = 0$	Sim_6	$\alpha = 1$	$\beta = 1$
Sim_2	$\alpha = 0$	$\beta = 1$	Sim_7	$\alpha = 1$	$\beta = 2$
Sim_3	$\alpha = 0$	$\beta = 2$	Sim_8	$\alpha = 2$	$\beta = 1$
Sim_4	$\alpha = 1$	$\beta = 0$	Sim_9	$\alpha = 2$	$\beta = 2$
Sim_5	$\alpha = 2$	$\beta = 0$			

Table 8 Results of selected simulations

Level of factor 1	Level of factor 2	Total profit (thousand $)								
		Sim_1 (0, 0)	Sim_2 (0, 1)	Sim_3 (0, 2)	Sim_4 (1, 0)	Sim_5 (2, 0)	Sim_6 (1, 1)	Sim_7 (1, 2)	Sim_8 (2, 1)	Sim_9 (2, 2)
1	1	90,891	93,941	87,910	105,129	83,619	109,526	102,352	87,189	81,777
	2	85,174	88,822	83,931	98,299	78,517	103,116	96,571	82,658	75,485
	3	80,807	83,933	79,753	90,873	70,591	95,940	90,448	73,570	67,727
2	1	82,315	88,233	83,764	99,783	80,510	104,091	101,434	85,909	76,868
	2	77,042	83,936	79,096	91,681	72,778	97,370	93,266	79,911	69,874
	3	71,966	78,642	73,958	85,650	65,962	88,969	87,730	72,711	62,895
3	1	73,915	81,637	78,254	93,356	75,489	98,778	98,574	83,877	73,032
	2	69,408	77,216	73,713	86,525	68,403	89,732	91,193	76,287	65,550
	3	63,774	73,086	68,516	80,022	63,015	84,706	84,510	72,761	61,206

results are summarized in Table 8. The profit gaps between Sim_6 and Sim_1 indicate that appropriate consideration of the trust value could be helpful to the performance of the supply chain. However, in some cases such as Sim_5, Sim_8, and Sim_9, excessive consideration of trust was harmful to the profit of the supply chain under specific independent factors.

To examine the effect of the input parameter α on the production plans and profit of the supply chain, Sim_1, Sim_4, and Sim_5 were compared. The details of the trust values, production plans, actual demands, and actual production of assembling plants A1 through A3 in Sim_1, Sim_4, and Sim_5 with independent factor levels (1, 1) are listed in Table 9. While plant capacity is utilized in the order of trust value in Sim_5, plant capacity is utilized in the order of cost efficiency in Sim_1. In Sim_4 and Sim_5, the capacity of A3 was not fully utilized due to the relatively low trust value. As α increases, there is an increasing preference for trustworthy partners, and the gaps between demand and actual production decrease. At the module manufacturer level, similar patterns are observed. While in-house assembling was preferred in Sim_1, the megasupplier M2 was preferred for all levels of independent factors in Sim_4. In Sim_5, the megasupplier M1, which has the highest trust value, was preferred. When the trust value is considered during production planning, important modules are outsourced to trustworthy partners in spite of their low cost efficiency.

Table 9 Trust value and feedback data of A1 through A3 with independent factor levels (1, 1)

		Trust value	Cost for C1, C2, C3 ($/unit)	Production plan for C1, C2, C3 (units)	Demand for C1, C2, C3 (units)	Actual production for C1, C2, C3 (units)
Sim_1	A1	0.975	7,150, 7,150, 7,300	0, 0, 190	298, 302, 301	0, 0, 172
	A2	0.905	5,150, 5,300, 5,300	330, 0, 70		303, 0, 65
	A3	0.830	4,300, 4,150, 4,300	0, 330, 70		0, 267, 54
Sim_4	A1	0.980	7,150, 7,150, 7,300	0, 0, 260		0, 0, 241
	A2	0.913	5,150, 5,300, 5,300	330, 0, 70	300, 303, 299	309, 0, 67
	A3	0.810	4,300, 4,150, 4,300	0, 330, 0		0, 272, 0
Sim_5	A1	0.968	7,150, 7,150, 7,300	330, 0, 70		318, 0, 67
	A2	0.903	5,150, 5,300, 5,300	0, 330, 70	302, 302, 303	0, 300, 64
	A3	0.821	4,300, 4,150, 4,300	0, 0, 260		0, 0, 220

Figure 9 illustrates the total profit of Sim_1, Sim_4, and Sim_5 for different levels of the independent factors. An examination of Fig. 9 reveals that, while Sim_4 shows better performance than Sim_1 for all levels of the independent factors, Sim_5 shows the worst performance. As listed in Table 10, the main causes of the profit gaps between Sim_1, Sim_4, and Sim_5 are the processing and back-order costs. Sim_1 shows the lowest processing cost and the highest back-order cost, while Sim_5 shows the highest processing cost and the lowest back-order cost. As α increases, the gaps between demand and actual production decrease. Decreased gaps yield a decrease of back-order costs. However, in Sim_5, in spite of lower back-order costs, too high processing costs cause the worst performance.

Figure 10 shows the reduction of total profit when the levels of independent factors change from a low level to a high level. Examination of Fig. 10 reveals that

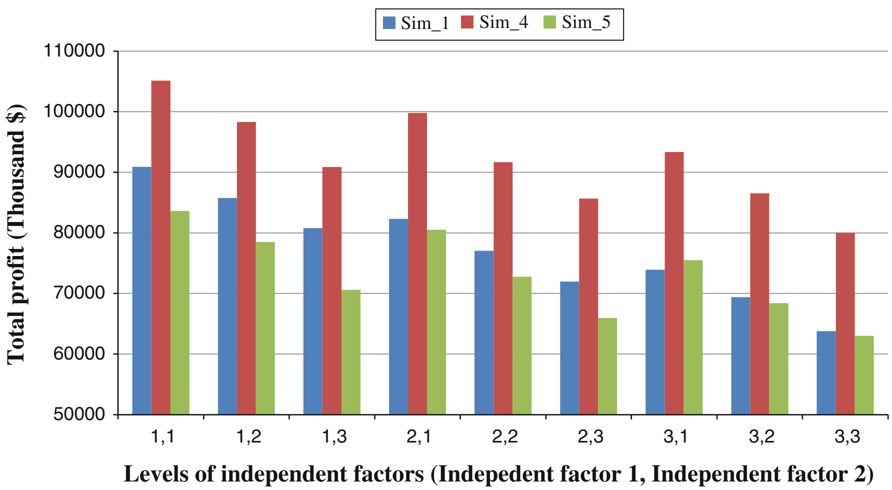

Fig. 9 Results of Sim_1, Sim_4, and Sim_5

Table 10 Detailed average costs (thousand $) in Sim_1, Sim_4, and Sim_5

	Processing cost	Inventory cost	Transportation cost	Back-order cost
Sim_1	52,131	21,346	12,822	35,835
Sim_4	65,341	19,128	15,906	15,261
Sim_5	80,238	18,253	19,043	13,874

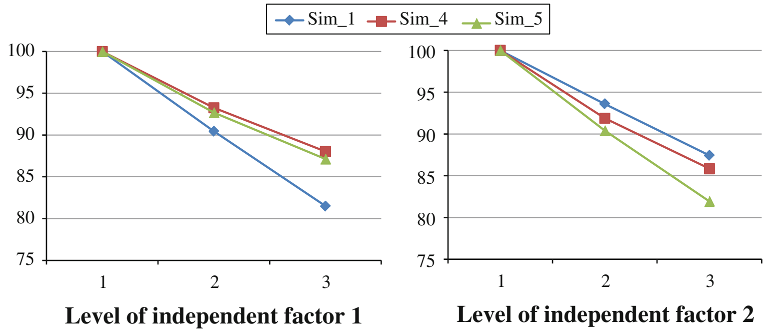

Fig. 10 Decrease in total profit in Sim_1, Sim_4, and Sim_5 according to the independent factors

the reductions of total profit under Sim_4 and Sim_5 are smaller than under Sim_1 when the variability in customer demand (independent factor 1) is increased; for example, while Sim_5 yields a profit reduction of 12.8%, Sim_1 yields 19.3% at the high level of variability. Based on the facts mentioned above, we can carefully conclude that consideration of trust factors is helpful in generating more precise production plans with regard to high demand variability in the illustrative supply chain. However, as shown in Fig. 10, the profit gaps between Sim_4 and Sim_1 decreased, and the profit gaps between Sim_5 and Sim_1 increased when the transportation cost (independent factor 2) was increased. This means that, as the cost against benefits increases, cost becomes a greater priority than before and the importance of trust factors decreases.

To examine the effect of the input parameter β on the profit of the supply chain, we compared the results of Sim_1, Sim_2, and Sim_3. Details of the trust values, safety stocks, and actually used safety stocks of assembling plants A1 through A3 in Sim_1, Sim_2, and Sim_3 are listed in Table 11. As β increases, the gaps between demand and actual production decrease.

Figure 11 illustrates the total profit of Sim_1, Sim_2, and Sim_3 for different levels of the independent factors. Examination of Fig. 11 reveals that Sim_2 shows better performance than Sim_1 for all levels of the independent factors. Sim_3 shows the worst performance when the level of independent factor 1 is 1. For other levels of independent factor 1, the total profit for Sim_3 is higher than that for Sim_1. As listed in Table 12, the main causes of the profit gaps between Sim_1, Sim_2, and Sim_3 are the inventory and back-order costs. Sim_1 shows the lowest inventory cost and the highest back-order cost, while Sim_3 shows the highest

Table 11 Trust value and safety stock data of A1 through A3 with independent factor levels (1, 1)

		Trust value	Level of safety stock	Actual safety stock (units)	Demand for C1, C2, C3 (units)	Actual production (units)
Sim_1	A1	0.975	10.0%	10	298, 312, 310	0, 0, 172
	A2	0.905	10.0%	40		303, 0, 65
	A3	0.830	10.0%	40		0, 267, 54
Sim_2	A1	0.976	2.4%	3		0, 0, 171
	A2	0.920	8.0%	32	307, 303, 289	301, 0, 60
	A3	0.822	17.8%	72		0, 257, 54
Sim_3	A1	0.969	6.2%	7		0, 0, 162
	A2	0.914	17.2%	69	310, 305, 312	296, 0, 62
	A3	0.836	32.8%	132		0, 253, 53

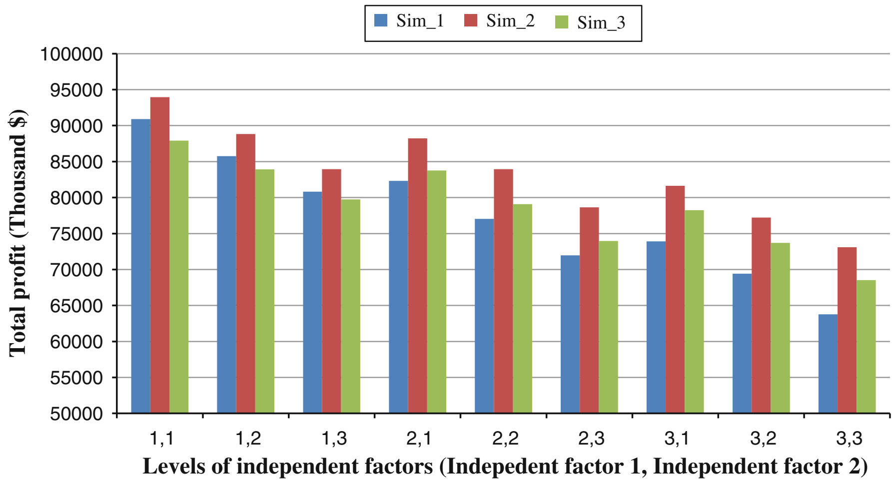

Fig. 11 Results of Sim_1, Sim_2, and Sim_3

Table 12 Detailed average costs (thousand $) in Sim_1, Sim_2, and Sim_3

	Processing cost	Inventory cost	Transportation cost	Backorder cost
Sim_1	52,131	21,346	12,822	35,835
Sim_2	51,104	23,647	12,921	30,969
Sim_3	52,574	32,753	13,539	27,349

inventory cost and the lowest back-order cost. As β increases, the back-order costs decrease and inventory costs increase.

Figure 12 shows the reduction of total profit when the levels of independent factors are changed from a low level to a high level. Examination of Fig. 12 reveals that the reductions of total profit under Sim_2 and Sim_3 are smaller than under

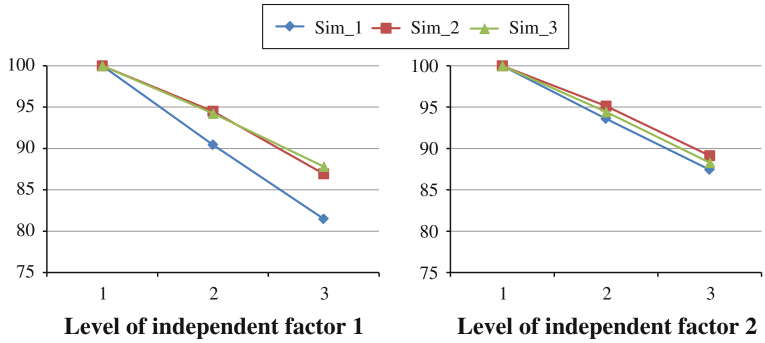

Fig. 12 Decrease in total profit in Sim_1, Sim_2, and Sim_3 according to the independent factors

Sim_1 when the variability in customer demand (Independent factor 1) is increased. Actually, it is a well-known fact that a high level of safety stock yields cost savings with wide fluctuations of customer demand. Independent factor 2 did not have significant impacts on the reduction of total profit in Sim_1 through Sim_3.

To examine the interaction effect between α and β on the profit of the supply chain, we compared performance for a given value of α under various values of β. Figure 13 plots the performance gaps for the various values of α according to the

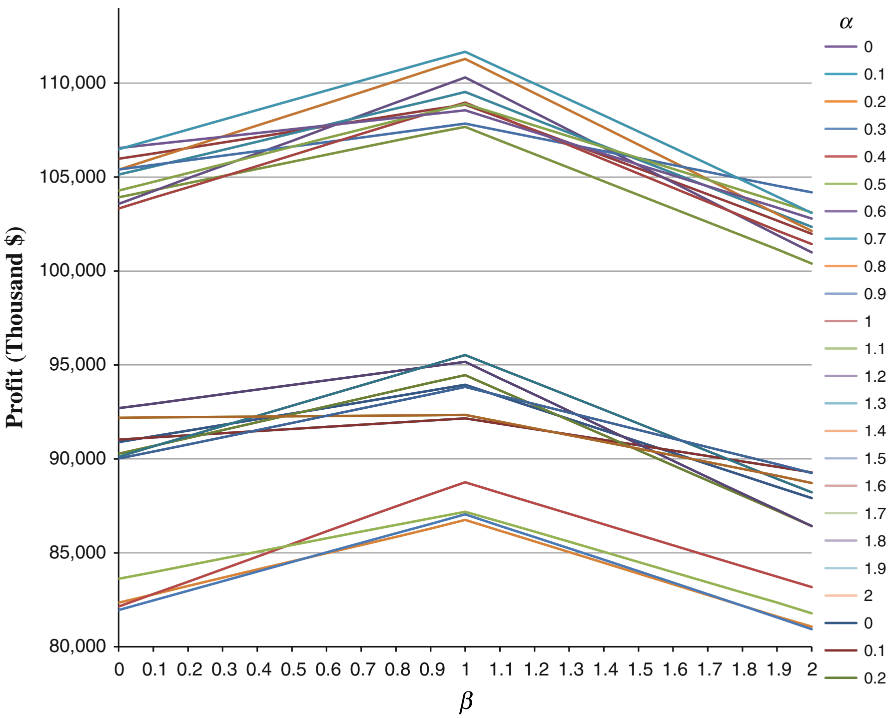

Fig. 13 Performance gaps for values of α according to the value of β

value of β when the level of independent factor 1 is 2 and independent factor 2 is 2. No significant changes of performance gaps are observed for the different values of β.

The results obtained here imply that consideration of trust values in production planning and determination of safety stock level are helpful to reduce back-order costs. As α and β increase, the back-order costs decrease for all levels of the independent factors. The contribution of α and β to the reduction of back-order costs is greater under conditions with high variability of customer demand, while the contribution is marginal for higher cost factors. As α increases, global trustworthy partners are preferred and the proportion of modularization increases. Excessive consideration of trust values could cause increase of processing costs because of poorly cost-efficient partners, and cause increase of inventory costs because of unnecessary safety stock.

In the proposed *c-f*SCM framework, the supply chain is decomposed into several fractals to distribute the computational load and time during optimization of production planning. To optimize production plans for the illustrative supply chain by using the mixed integer programming (MIP) approach, 330 integer variables and 500 constraints should be considered simultaneously. However, fewer variables and constraints must be considered, compared with the MIP approach, during a certain period of time under the *c-f*SCM framework, since they are distributed to subfractals. Table 13 compares the number of decision variables and constraints, and the computation time for production planning of the illustrative supply chain in the case of Sim_2. Distribution of decision variables and constraints reduced the computation time by about 46% for *c-f*SCM compared with the MIP approach.

6 Conclusions

In this paper, we have developed a *c-f*SCM framework for the automotive industry to consider the trust value in collaborations. In the new framework, the relationships between the participants of the supply chain are modeled as a fractal. Each fractal has a goal model and generates a production plan for its participants through

Table 13 Number of decision variables and computation time for production planning

		Number of decision variables	Number of constraints	Computation time (second)
MIP	Total	354	500	440
	Total	354	500	187
*c-f*SCM	*fr*_1 through *fr*_5	32 × 5	64 × 5	19 × 5
	*fr*_a1 through *fr*_a5	32 × 5	32 × 5	18 × 5
	*fr*_m1 through *fr*_m5	5 × 5	4 × 5	1
	*fr*_d1 through *fr*_d5	3 × 3	0	1
	Fractal_automotive	0	0	0

optimization of the goal model. There are three main advantages of c-*f*SCM while solving problems in SCM: (1) it becomes easy to understand and manage a complex system, (2) local optimization distributes the computational load and time, and (3) flexible management of supply chains is possible in the supply chain modeling phase. A detailed numerical model for the goal model was developed based on the profit model at each level of the fractal and the trust value of the participants in the supply chain. The trust evaluation model was developed using a fuzzy technique. The goal model and the trust evaluation model of the fractal were implemented using What's *Best!* 10.0 and Xfuzzy 3.0, respectively. To validate the developed framework for the automotive industry, simulations were conducted using AutoMod 12.2. The simulation results indicated that *c*-*f*SCM is useful for generating precise production plans in the illustrative supply chain and reducing back-order costs.

The main contribution of this research is that the trust value of participants was evaluated in numerical terms and considered in production planning. In the automotive industry, because the procurement ratio of parts from partners is very high, the *c*-*f*SCM framework can be used as an effective means of increasing the profit of the entire supply chain. Because the proposed *c*-*f*SCM uses local optimizations to optimize globally, it also helps to distribute the computational load for production planning. Especially in the automotive industry, it is very important to distribute or reduce the computational load, because of the large numbers of participants and components. For further studies, we are planning to extend the mathematical models to consider more factors related to supply chain performance. Additional simulations also need to be conducted to compare the proposed framework with various optimization techniques that have not been considered here because they are beyond the scope of this paper.

Acknowledgments This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science, and Technology (2009-0077660 and 2009-0087861). The authors would like to express their gratitude for this support. We also thank the editor and anonymous reviewers for their helpful comments.

References

Aigbedo H (2007) An assessment of the effect of mass customization on suppliers' inventory levels in a JIT supply chain. Eur J Oper Res 181:704–715

Akkermans H, Bogerd P, Doremalen JV (2004) Travail, transparency and trust: a case study of computer-supported collaborative supply chain planning in high-tech electronics. Eur J Oper Res 153:445–456

Alford D, Sackett P, Nelder G (2000) Mass customization-an automotive perspective. Int J Prod Econ 65:99–110

Angerhofer BJ, Angelides MC (2006) A model and a performance measurement system for collaborative supply chains. Decis Support Syst 42:283–301

Berning G, Brandenburg M, Gursoy K, Kussi JS, Mehta V, Tolle F (2004) Integrating collaborative planning and supply chain optimization for the chemical process industry (I)-methodology. Comput Chem Eng 28:913–927

Boersma K, Kingma S (2005) From means to ends: the transformation of ERP in a manufacturing company. J Strategic Inf Syst 14:197–219

Bullinger HJ, Faehnrich KP, Laubscher HP (1997) Planning of multi-site production: an objective-oriented model. Int J Prod Econ 51:19–35

Buzacott JA, Mandelbaum M (2008) Flexibility in manufacturing and services: achievements, insights and challenges. Flex Serv Manuf J 20:13–58
Childerhouse P, Disney SM, Towill DR (2008) On the impact of order volatility in European automotive sector. Int J Prod Econ 114:2–13
Currall SC, Inkpen AC (2002) A multi level approach to trust in joint ventures. J Int Bus Stud 33(3):479–495
Demeter K, Gelei A, Jenei I (2006) The effect of strategy on supply chain configuration and management practices on the basis of two supply chains in the Hungarian automotive industry. Int J Prod Econ 104:555–570
Fukuyama F (1995) Trust: social virtues and the creation of prosperity. Free, New York
Gnoni MG, Iavagnilio R, Mossa G, Mummolo G, Leva AD (2003) Production planning of a multi-site manufacturing system by hybrid modeling: a case study from the automotive industry. Int J Prod Econ 85:251–262
Handfield RB, Bechtel C (2003) The role of trust and relationship structure in improving supply. Ind Mark Manage 31:367–382
Iskandar BY, Kurokawa S, LeBlanc LJ (2001) Business-to-Business electronic commerce form first-and second tier automotive suppliers' perspectives: a preliminary analysis for hypotheses generation. Technovation 21:719–731
Ito T, Salleh MR (2000) A blackboard-based negotiation for collaborative supply chain system. J Mater Proc Technol 107:298–403
Jiao J, You X, Kumar A (2006) An agent-based framework for collaborative negotiation in the global manufacturing supply chain network. Robotics Comput Integr Manuf 22:239–255
Reeves KA Jr, Caliskan F, Ozcan O (2010) Outsourcing distribution and logistics services within the automotive supplier industry. Transp Res Part E 46:459–468
Koh SCL, Gunasekaran A, Cooper JR (2009) The demand for training and consultancy investment in SME-specific systems implementation and operation. Int J Prod Econ 122:241–254
Kwon IWG, Suh T (2006) Factors affecting the level of trust and commitment in supply chain relationships. J Suppl Chain Manage 40(2):4–11
Lane C, Bachmann R (1999) Trust within and between organizations. Oxford University Press, Oxford
Laosirhongthong T, Dangayach GS (2005) A comparative study of implementation of manufacturing strategies in Thai and Indian automotive manufacturing companies. J Manuf Syst 24(2):131–143
Lavravc N, Ljubivc P, Urbanvcivc T, Papa G, Jermol M, Bollhalter S (2007) Trust modeling for networked organizations using reputation and collaboration estimates. IEEE Trans Syst Man Cybernatics-Part C: Appl Rev 37(3):429–439
McCutcheon D, Stuart FI (2000) Issues in the choice of supplier alliance partners. J Manag 18(3):279–302
Moon IK, Goyal SK, Cha BC (2008) The joint replenishment problem involving multiple suppliers offering quantity discounts. Int J Syst Sci 39(6):629–637
Moore KR (2006) Trust and relationship commitment in logistics alliances: a buyer perspective. J Suppl Chain Manag 34(1):24–37
Msanjila SS, Afsarmanesh H (2008) Trust analysis and assessment in virtual organization breeding environment. Int J Prod Res 46(5):1253–1295
Mun J, Shin M, Jung M (2009a) A goal-oriented trust model for virtual organization creation. J Intell Manuf. doi: 10.1007/s10845-009-0293-7
Mun J, Shin M, Lee K, Jung M (2009b) Manufacturing enterprise collaboration based on a goal-oriented fuzzy trust evaluation model in a virtual enterprise. Comput Ind Eng 56(3):888–901
Panayides PM, Lun YHV (2009) The impact of trust on innovativeness and supply chain performance. Int J Prod Econ 122:35–46
Pierreval H, Bruniaux R, Caux C (2007) A continuous simulation approach for supply chains in the automotive industry. Simul Model Pract Theory 15:185–198
Qu X, Williams JAS (2008) An analytical model for reverse automotive production planning and pricing. Eur J Oper Res 190:756–767
Ryu K, Jung M (2003) Agent-based fractal architecture and modeling for developing distributed manufacturing systems. Int J Prod Res 41(7):4233–4255
Ryu K, Son Y, Jung M (2003) Framework for fractal-based supply chain management of e-Biz companies. Prod Plan Control 14(8):720–733
Sandanayake YG, Oduoza CF, Proverbs DG (2008) A systematic modeling and simulation approach for JIT performance optimization. Robotics Comput Integr Manuf 24:735–743

Schilli B, Dai F (2006) Collaborative life cycle management between suppliers and OEM. Comput Ind 57:725–731

Selim H, Araz C, Ozkarahan I (2008) Collaborative production-distribution planning in supply chain: a fuzzy goal programming approach. Transp Res Part E 44:396–419

Sucky E (2009) The bullwhip effect in supply chains: an overestimated problem? Int J Prod Econ 118:311–322

Warnecke HJ (1993) The fractal company: a revolution in corporate culture. Springer, Berlin

Author Biographies

Seungjin Oh is a Ph.D. candidate in the Department of Industrial and Management Engineering at Pohang University of Science and Technology (POSTECH), Korea. He received his B.S. degree in Industrial Engineering from POSTECH in 2004. His research interests include flexible and reconfigurable supply chain management and supply chain strategy.

Kwangyeol Ryu is an assistant professor of the Department of Industrial Engineering at Pusan National University (PNU) in Korea. He received his B.S., M.S., and Ph.D. from the Department of Industrial Engineering, POSTECH, Korea. His research interests include fractal-based approaches such as fractal manufacturing systems (FrMS), fractal-based supply chain management (*f*SCM), fractal-based virtual enterprises (FrVE), as well as innovative manufacturing technologies such as e-manufacturing, i-manufacturing, product lifecycle management (PLM), and next-generation manufacturing.

Ilkyeong Moon is a professor and head of the Department of Industrial Engineering at Pusan National University (PNU) in Korea. He received his B.S. and M.S. in Industrial Engineering from Seoul National University, Korea, and Ph.D. in Operations Research from Columbia University. He currently serves as the area editor, associate editor, and editorial board member for several international journals. He is a former editor-in-chief of the *Journal of the Korean Institute of Industrial Engineers*. His areas of expertise include production planning and control, supply chain management, and maritime logistics.

Hyunbo Cho is a professor of the Department of Industrial and Management Engineering at Pohang University of Science and Technology (POSTECH), Korea. He received his B.S. and M.S. degrees in Industrial Engineering from Seoul National University in 1986 and 1988, respectively, and his Ph.D. in Industrial Engineering with a specialization in Manufacturing Systems Engineering from Texas A&M University in 1993. He was a recipient of the SME's 1997 outstanding young manufacturing engineer award. His areas of expertise include business model creation, manufacturing management and strategy, and supply chain integration. He is an active member of the IIE and SME.

Mooyoung Jung is a professor in the School of Technology Management, Ulsan National Institute of Science and Technology (UNIST), Korea. He received his Ph.D. from the Department of Industrial and Manufacturing Engineering at Kansas State University in 1984. He has published more than 200 research papers in the fields of technology management and manufacturing systems. His current research interests include applications of fractal concepts to management and smart grid systems, and technology strategy and management for energy industry.