



CONSTRUCTION MATERIAL SUPPLY CHAIN PROCESS ANALYSIS AND OPTIMIZATION

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Abstract. This paper provides a systematic approach for the analysis and design of construction supply chain operation models. Based on the Supply Chain Operations Reference Model of the Supply Chain Council, this research studies supply and demand behavior, using a bridge superstructure construction process as a case study. This paper uses the SCOR Model and applies Dynamic Simulation software, namely, “SIMPROCESS”, to assist in establishing a hierarchical model to explore the behavior of the construction supply chain process and develop a performance evaluation method that can help improve the supply chain management (SCM) of the construction project.

Keywords: Supply Chain Operations Reference Model, Simulation, Construction project.

1. Introduction

There have been many recent improvements in construction technology, and a number of new construction technologies have been introduced in construction projects. However, of these new technologies have a higher cost, longer term durations and a more complicated construction interface. Material management is an issue often faced in construction projects. For example, in bridge superstructure construction management, even with unpredictable and complicated material demands, most box girder precast yards still use conventional procurement strategies to stock materials resulting in material backlogs, which not only complicates the environment inside the precast yard but also requires the reallocation of new space for material stacking. The use of conventional procurement methods may avoid material suspensions or shortages, but earlier materials entry in the precast yard increases not only the cost of material management but also the cost of repeated handling and interest loss due to excessive buy-ins of material. Solving these types of problems requires efficient construction project supply chain management. Successful methods of supply chain management (SCM) in other industries have been widely implemented in construction project management. Since construction production management is project oriented, the connections between contractors and subcontractors or suppliers are usually short-term relationships. However, without good SCM in construction project management there will be excessive costs, inefficient information

flow, and inefficient communication between project stakeholders. Vrijhoef and Koskela (1999) noted that the development of SCM in the construction industry is behind other industries due to a lack of systematic construction project supply chain design.

The Supply Chain Operations Reference model (SCOR Model), proposed by the Supply Chain Council (2004), is a complete business process and performance measuring method designed to meet customer demand from all perspectives. Through developing a supply chain model via SCOR in a hierarchical manner, and using multi-dimensional equivalent comparisons with respect to performance, the user can study the behavior of SCM from the model and implement an optimum plan, thus providing a standard quantitative analysis of process performance. SCOR aids in corporate internal and external system integration. SCOR can be also used to inspect current corporate performance against competitors, in order to improve performance.

This study put forward a set of systematic methodology for supply chain design and behavior analysis. SCOR was utilized to aid in supply chain design and behavior analysis, and in the founding of a set of supply chain models applicable to the construction industry, in an attempt to analyze and define supply chains in a systematic manner. The paper aimed to present a supply chain design and behavior analysis method to build a construction project supply chain model on the basis of SCOR, and study a series of demand-and-supply processes ranging from material purchasing, stocking and pro-

cessing to delivery, via a case study. The SCOR model assists developers in constructing an SCM model that provides the project's supply chain structure. The lack of a dynamic simulation function in the SCOR model indicates that users cannot identify and improve management problems of the project's SCM. Thus, this study integrates the SCOR model and dynamic simulation to create a novel construction supply chain model. The supply chain model is created using "SIMPROCESS" computer simulation software in a hierarchical manner, thus users can identify bottlenecks of the supply chain and enhance the performance of the construction project SCM.

2. Literature Review

Supply Chain Management (SCM) was a concept first proposed by Houlihan (1984), and it was an important development in corporate logistics. Initially SCM used the systematic dynamics concept and technique proposed by Forrester and Senge (2001) to deal with actual distribution and delivery operations, which points out that SCM is a dynamic management problem. The related studies of SCM on construction applications and SCOR in other industries' applications are illustrated below.

Pserng *et al.* (2006) proposed a supply chain model for rebar in a steel factory, optimizing their proposed model to minimize total inventory cost, and created a decision-support system for raw material suppliers, owners, and steel factories. Jeong *et al.* (2006) proposed applying SCM to production process control in the manufacturing industry, and considered it essential to business survival. However, after investigating SCM applications in the construction industry, Jeong *et al.* (2006) determined that SCM has not been utilized in the construction industry. Tah (2005) developed a computer program that allows users to create a computer simulation platform for a construction supply chain network and investigate the interrelationships and influences among construction supply chain members. Walsh *et al.* (2004) proposed that good SCM via simulation can allow precise material requirement planning (MRP) in advance to meet the

demands of the construction site and provide information such as quantity, specifications and the location of specific material deliveries to the project manager. The study by Houlihan (1984) noted that all construction projects may have similar processes, but each project is still unique. Klimov and Merkurjev (2008) investigated problems related to supply chain risk identification and simulation-based risk evaluation. Miao and Xi (2008) implemented artificial neural networks to present a quantitative forecasting method logistics demand in a dynamic supply chain environment. Janáček and Gábrišová (2009) formulated the problem of an enriched capacity facility, formalizing and studying the compactness of the location and suggesting a compound method to solve the problem. Miao *et al.* (2009) presented an uncertainty evaluation method that incorporated fuzzy rules and cloud theory to evaluate supply chain reliability (SCR), and verified it using a numerical example.

Based on the above studies, SCM has been proven to be a dynamic management problem. An efficient and effective SCM can improve time usage, cost control and the quality of construction project management. Also, via dynamic simulation technology, material cost control can be efficiently executed in the construction project management.

The Supply Chain Operations Reference model (SCOR Model) proposed by the Supply Chain Council is shown in Fig. 1. SCOR is the first standard reference model of the supply chain process, and its diagnostic tools cover all industries. Schultz proposed that SCOR structure development is meant to build partnerships on the supply chain and upgrade supply chain activity with IT technology, and SCOR can perform such functions properly in dynamic industries (Schultz 2003). Lockamy III and McCormack (2004) created a survey of SCOR execution performance, and the result showed that the *PLAN* step is the most important component of the SCOR model, measuring process, reliability, integration and information technology (IT), which are crucial in *Deliver* planning. Pundoor (2002) used simulation software, Arena, in compliance with the SCOR structure simulation

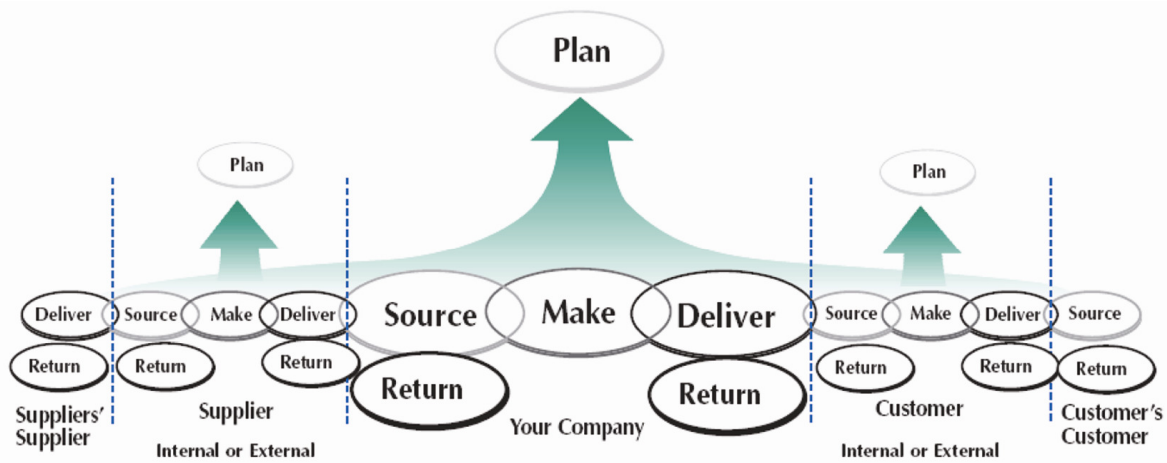


Fig. 1. Process type level (Supply Chain Council 2004)

model, to conclude that a shorter planning frequency gives rise to a better performance of the overall supply chain. The method proposed by Huan *et al.* (2004) is based on the SCOR performance structure, developed a method of measuring supply chain management. Sobotka and Czarnigowska (2005) showed that creating logistic guidelines for a project at its early stages of planning and then a designing an integrated logistic service may help make a construction project more effective. Based on the above studies, SCOR can help practitioners build organizational partnerships on the supply chain, and measure the performance of the supply chain. In addition, incorporating dynamic simulation technology with SCOR structure can help build a dynamic simulation model of a supply chain. Thus, the study implemented SCOR structure together with dynamic simulation technology to build a construction project supply chain model, and developed a construction project supply chain performance evaluation method to improve the performance of the construction project SCM.

SCOR subdivides the SCM process into five processes: Plan (*P*), Source (*S*), Make (*M*), Deliver (*D*) and Return (*R*). Demand and supply of these five modules were planned and controlled in detail. Based on fundamental elements of the processes, the basic elements of each step were established in a hierarchy. The relationships between various management steps were defined, a performance measure of each basic step was defined, the optimum solution of each basic step was defined, and applicable software features for each basic step were determined. Primarily used to measure and analyze supply chain structure, SCOR can help the supply chain stakeholders find management problems in the supply chain precisely, evaluate its property impartially, set periodic correction targets for problems, and even determine the trends of supply chain management software development. A SCOR model contains:

(i) Top Level 1 / Process Type

The first level of the SCOR plan defines and describes five fundamental processes and SCOR scope and content. (*Plan*: planning of the demand and supply balance; *Source*: process to source products or services; *Make*: process to turn materials into products; *Delivery*: process to provide products or services; *Return*: process for purchasing department to return materials or for distribution department to receive objected products)

(ii) Configuration Level 2 / Process categories

The second level of the SCOR model defines the configuration of the model. The SCM partner must choose the section type based on the section selected at the upper level. For example, under the *Make* section, the material supplier must, select its company operation strategy: *Make to Stock*, *Make to Order* or *Engineer to Order*.

(iii) Process Element Level / Level3

The third level of the SCOR model defines the process elements of the model. Every process type in level 2 is divided into detailed process units. Company or project descriptions detail each process step here, not only the processes under the process section, but also their relation

to external processes. Take the example of “*Source–Stocked–Product*” (code: S1): it is composed of 5 elements, namely, S1.1 (scheduling of material receipt), S1.2 (receiving material), S1.3 (checking material), S1.4 (stocking) and S1.5 (payment).

(iv) Implementation Level / Level 4

The fourth level in SCOR describes the implementation strategy of the models not defined in SCOR. SCOR only defines common standard supply chain reference structures to describe more detailed processes than the process element level. An SCM partner can implement specific supply chain management operations to respond to company environment changes.

(v) Performance Metric View

The SCOR Model provides a set of Metrics for the process level, *SCORCard*, as a reference for performance evaluation in SCM. The five metrics are *Reliability*, *Responsiveness*, *Flexibility*, *Cost* and *Assets*, respectively, which will be described more in section 3.3.

The paper presents a supply chain design and behavior analysis method, and the procedure is described as follows:

Step 1: The practitioners select a target construction project for supply chain behavior analysis.

Step 2: Based on the selected target construction project, the practitioners select one or several kinds of materials used in the project for supply chain behavior analysis.

Step 3: The practitioners build a dynamic supply chain model of the selected materials based on SCOR. The method of building the model will be described later.

Step 4: The practitioners screen key defect factors by interviewing relevant staff of the target case. After sorting out the SCM problems, the practitioners can implement the proposed SCORCard concept to design performance metrics to measure the case project’s supply chain behavior.

Step 5: Using the SCOR based dynamic model, the material management problems in the model can be identified. The practitioners can implement the proposed method to identify the best procurement alternatives for improving the SCM of the target project

3. SCOR-based construction material supply chain behavior analysis – a case study

This study selected a bridge superstructure construction project as a case study. The superstructure used box girders based on the Full-span Precast Method (FPM) under general conditions. The project needed over 500 spans and more than 3 years of construction before gaining any profit. Each box girder span made in the precast yard was 30 m to 35 m long and about 14 m wide, with an 800-ton maximum weight. The main construction material used in the project included steel bar (Steel bar), prestressed steel tendon (Steel tendon) and concrete (Concrete), accounting for over half of total material cost. In the raw material sourcing model, this study investigated the supply chain behavior of these three kinds of materials.

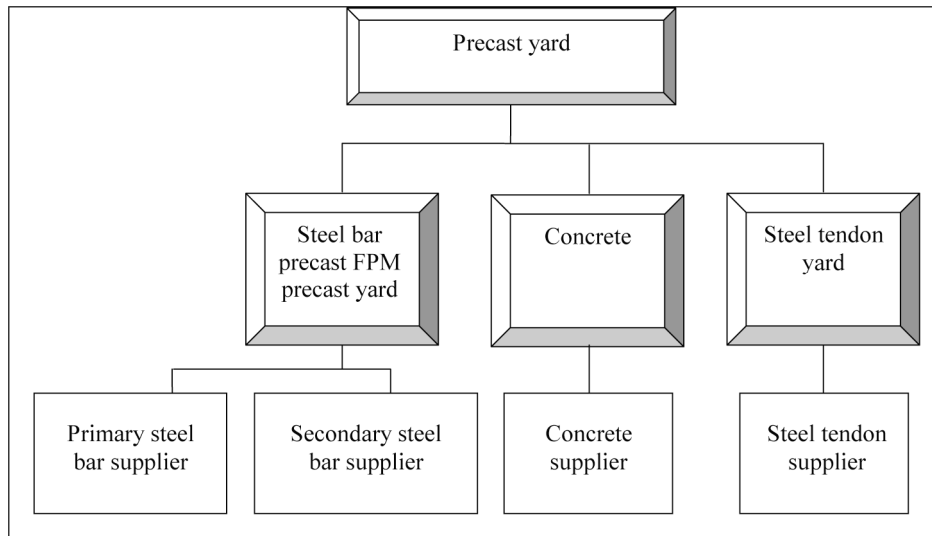


Fig. 2. Model structure of material supply chain in precast yard

Information flow and material flow exist in the supply chain. From the customer end (construction field) come calls to the precast yard (distributor) for material delivery. If the stock at this level cannot meet the demand, then the precast yard will order from raw material suppliers. Normally a precast yard will estimate the demand according to historical data or experiences, and place orders with the supplier in advance to avoid a shortage of material. A precast yard is normally composed of a steel bar yard, a premix yard and a steel tendon yard, and includes three primary materials: steel bar, skeleton, steel tendon, as shown in Fig. 2.

3.1. SCOR-based construction material supply chain model

Computer simulation software, SIMPROCESS, was used as a tool to build a construction project supply chain model based on the SCOR structure. SIMPROCESS (CACI Products Company 2004) is a hierarchical simulation tool with integrated functions, which can improve productivity using process analysis. SIMPROCESS can also integrate the functions of process mapping, hierarchical event-driven simulation and activity-based costing. It provides customized functions to append the program as required to meet various goals. As SIMPROCESS can consistently trace resource consumption, SIMPROCESS generally provides more accurate data than other statistic analysis methods. SIMPROCESS is based on Java and XML (Extensible Markup Language). These underlying technologies provide event-driven simulation capabilities, and hierarchical and dynamic expressions for modeling large-scale applications. Unlike hierarchical representations of processes using attached diagrams or files, SIMPROCESS offers true hierarchy based on object-orientation (Lockamy III and McCormack 2004).

Modeling using SIMPROCESS involves building all component symbols into a palette, which drags the modeling component in SIMPROCESS to a blank position and joins the components according to their input / output relationship with a connecting line. The main

components and their functions are compiled as listed in Table 3. From generation to disposition, a closed circuit is created. The main elements of SIMPROCESS include the following:

- (i) *Resource* – refers to consumptive resources, primarily steel bar, prestressed steel tendon, and concrete, which will decrease as the above materials are consumed, so order points and safety inventory measures will be set according to the status of the case, as indicated in Tables 1 and 2. *Entity* – Entity represents order flow from the precast yard to three kinds of material suppliers (steel bar, concrete, and prestressed tendon), and the flow of the manufacturing process.
- (ii) *Attribute setup (Global Attributes)* – SIMPROCESS will record the time every entity accesses each operation during simulation, recording quantity and related attributes so as to facilitate statistical analysis of table output. If an entity has the function of Transform or Split, its attribute relation before and after should be reproduced, as shown in Table 3.

SIMPROCESS makes a palette from all tool icons, drags tools via the mouse to a blank position, and connects tools with input and output relationships. From *Generate* to *Dispose*, a closed circuit is formed. The selection and deselection of tools denotes the process sequence.

The relationship structure of the construction supply chain members in the precast yard operation process was set up on the basis of SCOR Level 1, which defined the scope and content of the model as illustrated in Fig. 3. Every submodel is further discussed.

Steel bar procurement submodel

In steel bar sourcing, in accordance with the construction schedule and the amount stated in the contract, a precast yard will usually place an order with the steel bar manufacturer several days in advance, normally 21. To ensure a precast yard has no interruption of steel bar supply,

Table 1. Setup of related parameters of resource in model

Related parameters of resource	Resource name	Unit	Cost (NT\$)
Steel1	Steel bar provided by primary steel bar yard	ton	12000
Steel2	Steel bar provided by secondary steel bar yard	ton	11000
Steel tendon	Steel tendon	ton	17000
Con	Concrete	m ³	2600
RawSteel1	Raw material needed to make steel bar in primary steel bar yard	ton	
RawSteel2	Raw material needed to make steel bar in secondary steel bar yard	ton	
Raw Steel tendon	Raw material to make steel tendon	ton	
RawCon	Raw material of concrete	m ³	

Table 2. Information of consumptive resource

Material name	Statistics consumption cycle	Order cycle (unit: day)	Safety inventory	Delivery time
Steel bar	Monthly	Per 17~21	160 ton	Deliver in lots per month
Steel tendon	Monthly	Per 15~21	140 ton	Deliver in lots per month
Concrete	Daily	Daily	650 m ³	10–20 min

Table 3. Decision variables description

Decision variable name	Description	Unit	Order quantity
FinSteelOrderPt	Steel bar semiproduct orderpoint	Ton	160
Fin Steel tendon OrderPt	Steel tendon semiproduct orderpoint	Ton	200
FinConOrderPt	Finished Concrete orderpoint	Cubid meter	650

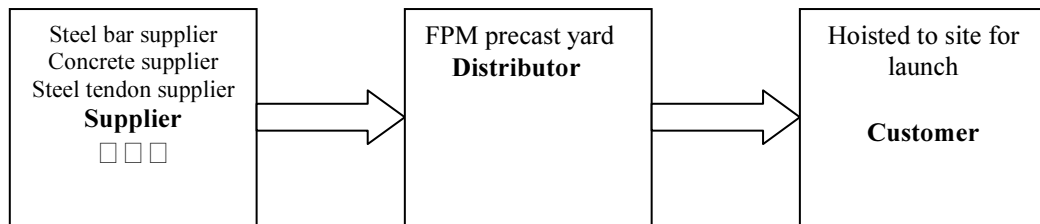


Fig. 3. Supply chain relationship of FPM process

generally at least 2 steel bar suppliers will be chosen. In the case study, one span consumed about 80 tons of steel bar. As the daily output of the steel bar manufacturer was 1700 t, the precast yard required the steel bar manufacturer to secure at least a one month safety stock in the precast yard. The daily stock level of steel bar needed to contain the amount required for two spans of box girders, about 160 t.

The steel bar supply chain procurement submodel primarily included three levels of operation models, as stated below:

Level 1 (Top level/Process type level): included 5 sub processes.

Plan: the process to plan the balance of supply and demand. The project department had to plan the quantity of steel bars to order according to the construction schedule and total inventory.

Source: the process to procure steel bar. The precast yard would order, with 21 days notice, the quantity and size of steel bars needed for the next month. Sourcing was made on multiples of the estimated steel bar quantity.

Make: the process to make material into product. Rebar was cut into required sizes for further processing.

Delivery: the process by which steel bar supplier deliver steel bar to the precast yard.

Return: the process to reject and return unqualified steel bars.

Level 2 (Configuration level2/Process category level):

P2 “Plan Source”: the time the project department placed an order was set at 20 days, and the order quantity was determined by distributing orders based on the historical data via statistics software, namely, StatFit2. The information flow was as follows: query the steel bar storage yard if the remaining safety inventory of steel bar is enough. If yes, then deliver it to the field construction first. If not, or if material is shipped, the inventory will drop to the order threshold leading to shortage, needing the stock to then be replenished by sourcing steel bar. The steel bar supplier receives the order, and delivers material out of stock, which is then delivered to the precast yard. To prevent this circumstance, normal precast yards will

estimate future consumption and place orders with the supplier in advance, according to the historical data.

S1 “*Source Stocked Product*”: the process to predict the construction schedule and replenish safety stock before sourcing steel bar material. SCOR defines “*Source Stocked Product*” as S1.

M3 “*Engineering to Order, ETO*”: the process by which the precast yard sources steel bar according to the construction schedule, size and quantity requirements, and cuts it in the steel bar yard.

D1 “*Deliver Stocked Product*”: the process by which the steel bar supplier delivers steel bar to the precast yard, at least 25 tons per truck. If less than 25 tons were delivered, the freight would be compensated. Two suppliers provided steel bar at the same time to cater to demand fluctuations, with the primary supplier responsible for 70% of the demand and the secondary supplier providing the other 30%.

SR1 “*Return Defective Product*”: the process by which steel bars are delivered to the site, and checked for quality. Steel bars that were disqualified were disposed of as waste, with concrete and steel tendon treated alike. Qualified steel bars and disqualified ones were discriminated in probability. According to the incoming acceptance report of C260 steel bar provided by “Han Tai Steel Bar Co., Ltd.”, the defect rate was 0.00001, hence steel bar defect occurrence probability in the system was set at 0.00001.

Level 3 (*Process element level*):

S1.3 “*Acceptance*”: the process according to the contract between the Taiwan High Speed Railway company and the civil engineering contractor. It was explicitly defined that the construction material was to be sampled and tested. The main material in connection with the box girders was steel rebar, Portland cement, prestressed anchorage and prestressed strand, and the related testing items and methods were as per CNS and ASTM. Prior to construction, the contractor would submit material supplier certifications, test credentials, equipment and capacity of the manufacturer or premix yard to the Taiwan High Speed Railway company for supplier qualification, inspection, concrete mix ratio design, premix and field mix operations. Only after being verified to comply with requirements and acquiring a “non-dispute statement” could the material be permitted to enter the field.

S1.4 “*Material admission*”: a material acceptance test was administered in the precast yard.

Concrete procurement submodel

As concrete sourcing was subcontracted to a professional concrete supplier, the precast yard did not need to be involved, provided that the raw material used by the concrete supplier complied with the specifications in contract, and the concrete reached the designed strength. To ensure no supply shortage from the concrete supplier, the precast yard required the concrete supplier to have at least a one-month safety inventory. The designed concrete amount for a 35 m spanned precast box girder was 320 m³, so the inventory level of the precast yard required concrete material for two spanned box girders.

The concrete supply chain operation submodel also included three level operation models as stated below:

Level 1 (*Top level/Process type level*): Since concrete was subcontracted to the premixed concrete supplier, there was no need to *Make* concrete in the supply chain operation process, which defined 4 subprocesses including *Plan, Source, Delivery, and Return*.

Plan: the process to plan the balance of supply and demand, especially timely delivery to the precast yard was very important for concrete usage, thus the project department had to plan the quantity of concrete to order according to the construction schedule and total inventory.

Source: the process to procure concrete. The precast yard needed to place the order according to the construction schedule.

Delivery: the process by which the concrete supplier delivered concrete to the precast yard.

Return: the process to reject and return unqualified concrete.

Level 2 (*Configuration level 2/Process category level*):

P2 “*Plan Source*”: Concrete usage planning should conform to ASTM C94 specification. Of particular importance is the elapsed time from the introduction of water to the placement of the concrete in the forms. ASTM C94 allows a maximum of 1.5 hr, or before the drum has made 300 revolutions, whichever comes first. Thus, the concrete sourcing period used “day” as the ordering time unit. Consequently, the ordering quantity distribution was set by a triangular distribution expressed by Tri (306.0,459.0,612.0,1). The syntax used in SIMPROCESS was Tri (minimum, mode, maximum, stream).

S1 “*Source Stocked Product*”: The sourcing concrete would be conducted from the concrete supplier according to the construction schedule.

D1 “*Deliver Stocked Product*”: The concrete supplier delivered concrete to the precast yard for mixture, and the transport truck amount was based on the transit mixer’s size. The command for controlling the *Entity*, “*Deliver Stocked Product*”, using SIMPROCESS is described as follows:

$$A.W. = A.W. + E.W.;$$

where A.C. denotes the accumulated weight of ready transited concrete, and E.W. denotes the entity weight of the ready transited concrete.

$$\text{IF } A.W. > 19 \text{ m}^3.$$

$$\text{MaxBatchSize} = \text{NumberIn};$$

where MaBatchSize denotes the maximum batch size of the concrete transporter END IF;

SR1 “*Return Defective Product*”: The process to return the defective product would be conducted if the delivered concrete did not conform to the ASTM C94 specifications.

Level 3 (*Process element level*):

S1.3 [acceptance]: Test of concrete performance or receipt by the precast yard.

S1.4 [material admission]: Concrete passing the acceptance test was admitted to the precast yard.

Steel tendon procurement submodel

As the prestressed system dictated using a prestressed steel tendon supplier of the same system, only one supplier was selected in most cases, according to the five perspectives of the SCOR process type level. The prestressed steel tendon sourcing operation model was set up similar to the steel bar sourcing model, which will not be detailed herewith.

The steel tendon procurement submodel primarily included three levels of operation models as stated below:

Level 1 (Top level/Process type level): define 5 sub processes.

Plan: the process to meet the demand of supply and demand planning. The project department had to calculate the steel tendon quantity to order according to the construction schedule and the inventory level.

Source: the process to procure steel tendon. The precast yard would order, with 21 days notice, the quantity and size of steel bars needed in the next month, with sourcing made on multiples of the estimated steel bar quantity.

Make: the process to make a product into a finished product, in this case meaning to cut steel tendon into required sizes for further processing.

Delivery: the process by which the steel bar supplier delivered steel tendon to the precast yard.

Return: the process to reject unqualified steel tendon, and return material to the supplier.

Level 2 (Configuration level 2/Process category level):

P2 "Plan Source": Steel tendon usage planning was based on the construction schedule. The quantity requirement estimated statistical distribution was set by a normal distribution expressed by $N(\mu, \sigma)$ (138.495, 45.6377, 1) according to data collected from 2001/10/31 to 2003/8/31. The data was analyzed using Statfit, and the syntax used in SIMPROCESS was Nor(mean, standard deviation, stream). Consequently, the FPM precast yard would decide to place the order according the above schedule data and inventory information.

S1 "Source Stocked Product": if the inventory were insufficient, the FPM precast yard would place the order with the supplier.

M3 "Engineering To Order, ETO": the precast yard sourced steel tendon according to the construction schedule and size and quantity requirements, and cut it in the steel tendon yard.

D1 "Deliver Stocked Product": the process by which the supplier delivered steel tendon to the FPM precast yard.

Level 3 (Process element level):

S1.3 "Material admission": the quality test before the steel tendon was implemented.

S1.4 "Acceptance": a steel tendon acceptance test was administered in the precast yard.

The superstructure operation submodel

The superstructure operation submodel primarily described a level 1 SCOR model in the study due to the complexity of construction as stated below:

Level 1 (Top level/Process type level): defined 2 sub processes.

Plan: the process to plan resource requirements including steel bar, concrete, and steel tendon. The FPM precast yard usually produced one to two box girder spans per day, thus the maximum capacity in the model was set at two spans per day.

Make: Chiu *et al.* (2000) pointed out that the critical point of this method is to streamline the whole box-girder production process, including the operations of reinforcement cage prefabrication and precast box-girder production. The non-prestressed reinforcements, such as web, deck slab, and bottom slab reinforcing bars, are assembled and spot-welded first. After cleaning the outer form, the steel tendons are allocated in the settled reinforcement cage and thus pulled through the pull-head. Next, the steel tendons are pre-stressed using the pre-tension method, which is particularly economical among prestressing methods. Then High Performance Concrete (HPC) is placed onto the casting bed. After an initial setting of the concrete, steam curing proceeds. Consequently, the inner mould slips out of the box-girder and the stripping hang-beam is installed. The prestressed strands outside both ends of the girder are relaxed and cut consequently. Next, the precast box-girder will be stocked in the storage area.

Model test

The accuracy of the model simulation was verified by the behavior reproduction test. The simulation result analysis covered the comparison of capacity and schedule, and the resource utilization rate between actual data from the case study and the proposed model simulation results. The research compared the result above with the simulation results of the proposed model. The bridge substructure construction progress was influenced by weather, geographic conditions, safety accidents and site conditions. Thus, the proposed model simulation results compared with the real substructure production behaviors were not exactly the same, as shown in Fig. 4. However, after a behavior reproduction test, the simulations results proved the accuracy of model production behavior simulations in major bridge components.

3.2. Material procurement behavior optimization

After creating the SCOR model using SIMPROCESS, it was necessary to identify material management problems in the model. One of the largest problems in the case study was material overstocking in the construction field. The construction field often kept construction materials on hand to meet demands on time. However, inefficient procurement strategies, such as overstocking resulted in the increase of unnecessary inventory costs. The study used SIMPROCESS's optimization tool, OptQuest, to identify the best procurement alternatives in the model and examine whether the procurement strategy FPM used in the precast yard was appropriate.

OptQuest is an optimization tool that attempts to minimize or maximize the value of a performance measure based on limits (constraints, upper bounds, and

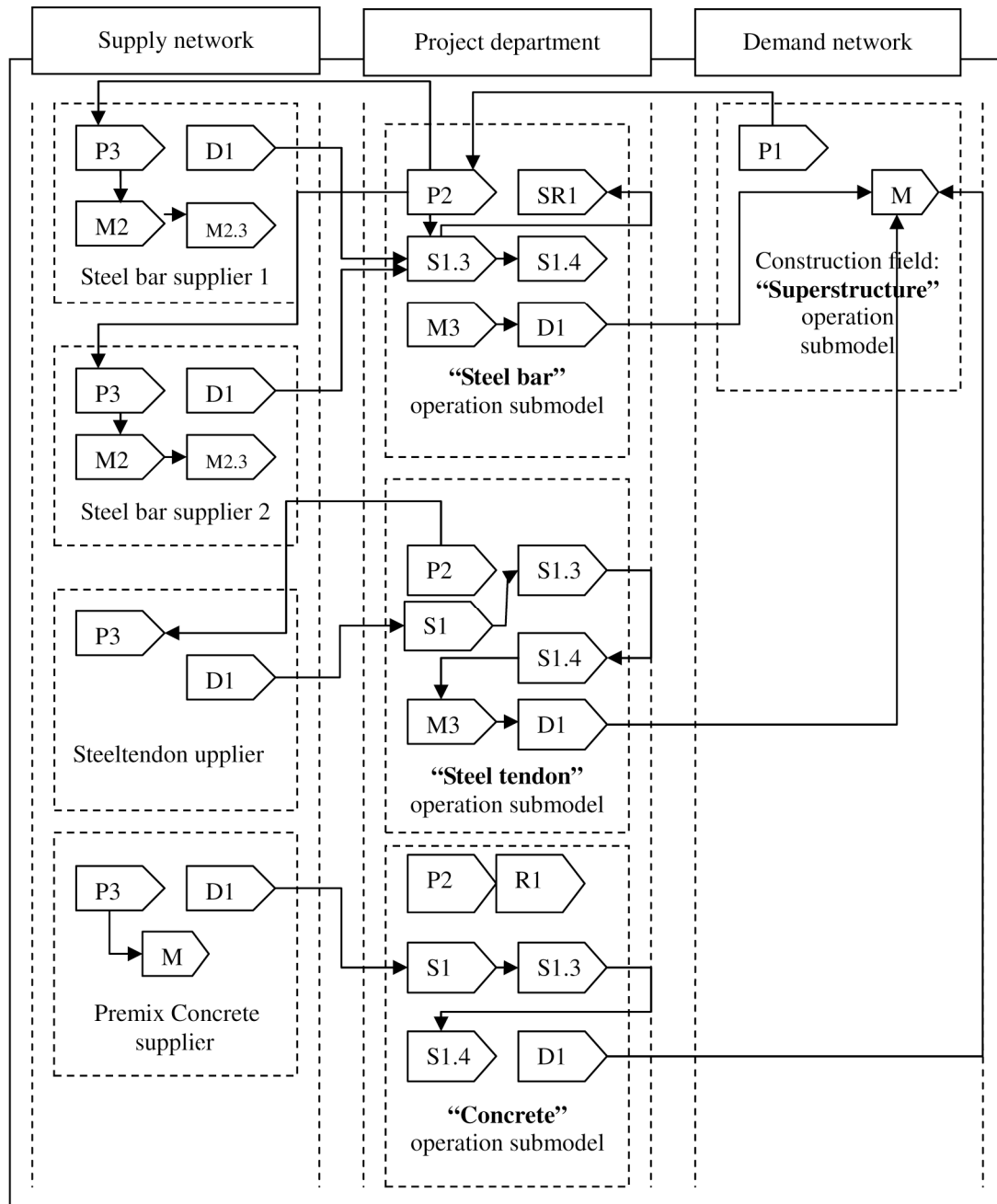


Fig. 4. Schematic of supply chain operation model of the High Speed Rail

lower bounds). OptQuest automatically runs the SIMPROCESS model, varying the values for the model parameters and searching for optimum results using its intelligent search procedures within the specified limits. The elements of an OptQuest optimization consist of an objective (minimize or maximize), decision variables, and constraints, which are optional. The OptQuest procedure in SIMPROCESS is described as follows:

1. Establish a simulation model, then generate an initial solution and set as $f(x)$, wherein X is the simulation result, which can be taken as an initial solution of OptQuest. Take X as an input parameter of OptQuest (Met heuristic Optimizer), and set as X^* if a new test solution is generated during the search process.

2. The best solution found until now is represented by x^* .
3. Set $f^{\wedge}(x)$ as the objective function. It is required if the objective function to be searched is a maximum or minimum value.
4. The $f^{\wedge}(x)$ value is solution X evaluated from the met model.
5. Set the original solution of the objective function as X . If there is a new solution X^* after OptQuest, X^* is substituted into X .
6. Filter d to check if the solution meets the objective solution as required (an example of minimization), with the calculation process shown below:

Parameter	Starting Value	Lower Bound	Upper Bound	Step Size	Include
FinSteelOrderPt	160	80	800	10	<input checked="" type="checkbox"/>
FinrollsteelOrderPt	200	150	300	10	<input checked="" type="checkbox"/>
CompSteelReOrderPt	4200	4000	10000	10	<input type="checkbox"/>
CompConReOrderPt	19500	19000	40000	10	<input type="checkbox"/>
ComprollSteelOrderPt	528	528	1000	10	<input type="checkbox"/>
FinConOrderPt	650	600	1000	10	<input checked="" type="checkbox"/>
CompSteelReOrderPt	3600	3600	6000	10	<input type="checkbox"/>

Fig. 5. Decision variables input menu in Simprocess

$$d = f^{\wedge}(x) - f(x), \tag{1}$$

where: X – new solution, X* – optimal solution, f(x) – function obtained from simulation, f^{\wedge}(x) – objective function, d – detection condition.

If the result of minimization is bigger than d, x must be further considered for removal. If the result is smaller than d, conduct simulation, OptQuest and target value comparisons repetitively until all searched solutions are the same.

Objective

In the study, the objective of the inventory model optimization problem is formulated as following:

Minimize

R.C.

where the objective

$$R.C. = \text{Steel1Cost} + \text{Steel2Cost} + \text{Steel tendonCost} + \text{ConCost};$$

$$\text{Steel1Cost} = \text{Steel1 P.C.} + \text{Steel1 I.C.};$$

$$\text{Steel2Cost} = \text{Steel2 P.C.} + \text{Steel2 I.C.};$$

$$\text{Steel tendonCost} = \text{Steel tendon P.C.} + \text{Steel tendon I.C.};$$

$$\text{ConCost} = \text{Concrete P.C.} + \text{Concrete I.C.},$$

where R.C. denotes the entire resource capacity cost, Steel1Cost denotes the resource cost of the primary steel bar, Steel2Cost denotes the resource cost of the secondary steel bar, P.C denotes the purchase cost, and I.C. denotes the inventory cost.

Decision variables

The decision variables of the inventory model optimization problem are based on the influence of the model’s objective, as shown in Table 3. Using performance measure constraints, the model users enter an Upper Bound and a Lower Bound data, which is based on the actual material requirements of the schedule, as shown in Fig. 5.

An optimal solution of the inventory model can be obtained using the OptQuest function of SIMPROCESS that is recorded in the system, namely TO-BE. The TO-BE recorded in the system as a benchmark (*target*) that can be compared with the actual procurement plan in the case, namely AS-IS, for SCM performance evaluation and improvement purposes. If AS-IS is higher than TO-BE, there is a need to reduce unnecessary inventory to save the holding cost. In the following section, the paper will analyze the case’s SCM performance using TO-BE and AS-IS.

3.3. SCM performance analysis of the case study

An important purpose of the study was to identify the performance metrics that influence supply chain performance. Inappropriate or unnecessary performance metrics do not help evaluate SCM performance. After screening key defect factors using interviews of relevant staff during the construction of the Taiwan High Speed Rail and sorting out the SCM problems, the study implemented the SCORCard concept to design performance metrics for the construction SCM. The objectives of the SCM were to reduce the SCM networks’ overstock cost. Therefore, based on the SCORCard and the construction project’s characteristics, the construction performance metrics in the study included two phases; cost and reliability, which are discussed in more detail later.

SCOR-based supply chain performance analysis can be divided into 4 steps (as shown in Fig. 6): define measures according to current supply chain performance, interpret them, set up the *SCORCard*, and analyze defective factors in the SCM.

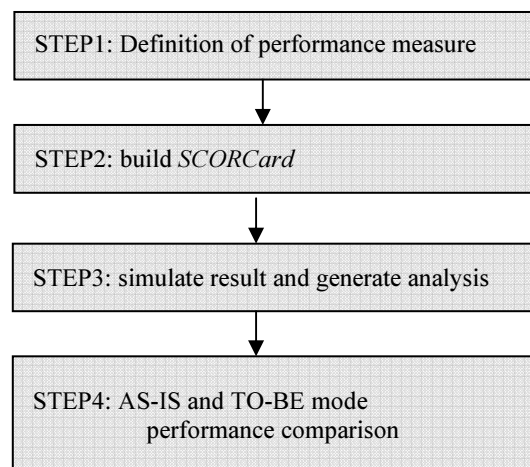


Fig. 6. Flow chart of supply chain performance analysis

The *SCORCard* can be divided into five dimensions: *Supply Chain Delivery Reliability*, *Supply Chain Responsiveness*, *Supply Chain Flexibility*, *Supply Chain Cost* and *Supply Chain Assets Management Efficiency*. It was known from staff interviews that the HSR project had high requirements of material quality. Timely product delivery was also a crucial factor for the overall supply chain. Due to the large construction cost of the HSR project, unnecessary material waste would cause

great losses for the contractor. Thus, two perspectives, *Cost* and *Reliability* were selected, as well as three representative performance indexes and definitions in SCM, *stock interest cost loss*, *product failure rate*, and *safety stock*, as shown in Table 4.

Table 4. Definition of performance metric initially classified

Perspective	Description of metric	Definition
Cost perspective	Inventory cost	Capital backlog cost and interest cost of non-consuming material
Reliability perspective	Product failure rate	Defective product after inspection
	Inventory status	Optimum safety inventory

The following describes the process to select the two perspectives and the three performance indexes, and the analyses of the SCM performance of the case study through the *SCORCard*.

Supply Chain Cost perspective

This paper studied the case of safety stock in the precast yard to prevent supply interruptions and temporary shortages. Unused raw material piled up in the precast yard is a capital cost, and the higher the inventory, the higher the capital cost, causing the contractor greater stress in turnover and leading to interest loss. The inventory cost is the unit interest cost of the raw material multiplied by its stock amount.

Supply Chain Delivery Reliability perspective

For the delivery reliability perspective, the study selected two performance metrics: product failure rate and inventory status. After raw material was delivered to the precast yard, the material quality had to meet the contract requirements, related test items and methods conforming to CNS and ASTM. Therefore, the performance metric for the product failure rate could be used for evaluating the SCM delivery quality. Also, meeting the safety stock level and reducing the risk of material shortage is an important issue in SCM. Thus, inventory status was selected as the other performance metric for the delivery reliability perspective.

Analysis of SCORCard

In order to build a balanced *SCORCard* from verified supply chain measures, a pair of process level measures in SCOR were referenced to measure the performance in the company, and these levels were the elements used to measure the SCOR metrics and process as shown in Table 5.

Table 5. *SCORCard* specification

SCOR card --- (Type Name)									
Level	Metric	SCOR Definition	SCOR Categories	MyCom Definition	MyCom Categories	Actual	Target	Gap	Gap Rate

Column 1, *Level*, represents the metric level in SCOR. Column 2, *Metric*, is the description of this performance metric. Column 3, *SCOR Definition*, is the SCOR-defined performance metric. The company could choose appropriate metrics according to SCOR, and fill them in columns. The fourth column, *SCOR Categories*, contains SCOR information about what functions each metric was related with, which was then input in the SCOR Categories. The next column, *MyCom Categories*, is the current SCM status, in which went into column 7, *Actual*. Performance targets are defined in Column 8, *Target*. Column Gap refers to differences between *Actual* and *Target*. The data contained in *Gap Rate* could be marked by operators for further discussion. The gap was usually less than 0.1 in the case study, thus the difference between current status and target was known.

SCORCard setup

Cost category (Table 6): the “stock cost” metric was categorized into three submodels, including steel bar operation, steel tendon operation, and concrete operation. The performance definition was described in the steel bar yard cells. In the Categories cells, SCOR correlation enabled company measures to correspond with each other, e.g., steel bar yard stock was located in the SCOR Level 1 Model (*process type level*), indicating control at P2 (*material planning*) in SCOR level 1. The user could then find failure points in the Categories cells.

Continuing the process described before, convert the average inventory discovered during the personnel interviews to the interest loss and to Actual value, then fill the preset target stock cost in the *Target* cell. The column Gap refers to the difference between *Actual* and *Target*. *Gap Rate* calculates the ratio of gap over target, which can help to better understand the case’s SCM status.

If the *Reliability type* (Table 7) Categories and Definitions were the same as *Cost*, then column *Actual* was filled in with unused inventory, filling the safety inventories of three kinds of material in the cells, while *Target* was the preset safety stock level, and column *Gap* referred to the difference between initial inventory and safety inventory. The *Gap Rate* was $Gap/Actual$.

Simulation result analysis

The previous supply chain operation model *SCORECard* was built with two perspectives: *Cost* and *Reliability*. In the Reliability category, the failure rate of steel bar calculated from the case was filled in *Actual*, and observations based on the modeling result were performed to see if the daily material inventory in the precast yard met the prescribed safety inventory.

Table 6. Cost category *SCORCard* of company in the case study

SCOR card (Cost)						
Metric	Definition	Categories	Actual	Target	Gap	Gap Rate
Stocked cost (steel bar yard)	Yard backlog cost	P2 material planning SCOR Level1 Model	108,302	83,934	24,368	0.225
Stocked cost (steel tendon yard)	Yard backlog cost	P2 material planning SCOR Level1 Model	134,246	114,109	20,137	0.15
Stocked cost (concrete yard)	Yard backlog cost	P2 material planning SCOR Level1 Model	95,355	88,167	7,188	0.075

(Unit: NT\$)

Table 7. Reliability category inventory *SCORCard*

SCOR card (Reliability)						
Metric	Definition	Categories	Actual	Target	Gap	Gap rate
Inventory (steel bar yard)	Stock status	P2 material planning SCOR Level1 Model	160	124	36	0.225
Inventory (steel tendon yard)	Stock status	P2 material planning SCOR Level1 Model	140	119	21	0.15
Inventory (concrete yard)	Stock status	P2 material planning SCOR Level1 Model	650	601	49	0.075

(i) Reliability type

Steel bar failure rate: in the *SCORECard* steel bar failure rate, all data in the column Gap Rate greater than 0.1 were marked by operators for further study, as the statistical failure rates did not exceed the *Gap Rate* threshold of 0.1, and the Taiwan High Speed Railway had stringent requirements for material. The steel bar yard would check twice internally before shipping, so the steel bar pass rate was as high as 99.9%, with the defect rate relatively lower at 0.01%. Here, its performance was deemed acceptable, and was therefore not further discussed.

Inventory (steel bar): the daily steel bar stock level in the precast yard was so set that it could make 2 spans or more of box girders, or about 160 tons. The daily stock was set as the *Actual* value. Using TO-BE via OptQuest in the *Target* column showed a daily stock of 124 tons. The difference was 36 tons, as shown in the *Gap* cell. The *Gap Rate* was obtained by $Gap/Actual$, resulting in a *Gap Rate* of about 0.225, larger than the threshold of 0.1, meaning inventory was still high, therefore system operators had to further consider the need to lower inventory.

Inventory (steel tendon): the method to measure the performance was the same as that for steel bar. However, from the results of the interviews, it was learned that the precast yard had a weekly stock level of about 140 tons, and was possibly overstocked. It was known from the *SCORCard* that the score was greater than the threshold of 0.1, so it was recommended to lower the inventory according to the optimization result, which was to decrease the inventory level to about 119 tons, or the level needed for 5 days.

Inventory (concrete): the concrete stock level in the precast yard was so set that it could make 2 spans of box girders, or about 650 m³. As the concrete warehouse had limited space, and concrete had been subcontracted to a professional concrete supplier, the material stock and optimization results varied little. As the *Gap Rate* was

less than 0.1 (threshold), the inventory did not need to be decreased.

(ii) Cost type

The construction material sourcing cost was the quantity of material to be used in actual construction multiplied by its unit price in sourcing. The safety inventory was set in the precast yard to prevent temporary shortages. Raw material stacked in the precast yard was deemed as a capital cost; the larger the inventory, the higher the capital cost, causing the contractor to have high pressure in capital turnover and suffer interest loss. The material stock cost was the unit interest of the raw material multiplied by its inventory.

Steel bar:

Interest of steel bar per ton per month (unit: US dollar) =

The price of steel bar per ton $\times (1 + \text{interest rate}/12)^{12}$ – unit price of steel bar = \$19.33/month/ton,

As for Actual,

Stock cost of steel bar per year = steel bar stock \times interest of steel bar = 160 (ton) \times 19.33 = \$3094.35 per month.

As for Target,

The optimum safety inventory 124 (ton) \times interest of steel bar = 124 \times \$ 19.33 = \$ 2,398.16 per month, Gap value was the difference \$ 3094.35 – \$2,398.16 = \$696.23,

Gap Rate threshold is \$ 696.23 / \$ 3094.35 = 0.225.

With respect to “cost” only, the smaller the value, better it would be. The *Gap Rate* obtained from the *SCORCard* was more than 0.1, which required further inventory cuts and cost reductions.

Table 8. SCOR Analysis Table

Without SCOR	With SCOR
Conventional supply chain management program does not take the overall supply chain into consideration; member communication is difficult when voiding the overall supply chain.	Operation reference model of Supply Chain Association has consolidated the standard for many industries, enhancing the synergy of the company and its partners.
Susceptible to cause ambiguous role definition of supply chain members.	Use 5 management process elements to define relations between various management processes and determine the levels.
Varied definitions of supply chain evaluation	Provide 5-perspective process level structures for reference to the organization or project performance evaluation.
Lack of information visibility	Encode process category systematically, enhance information visibility in the supply chain.

Steel tendon: the method to measure to SCM performance was the same as that for steel bar, yet the unit price of stocked steel tendon was higher. Though the overall stock price was greater than that of steel bar, the overall stock status and interest lost were better than the Gap Rate of “steel bar”.

Concrete: as it didn't exceed the threshold of 0.1, it was construed as having good performance, and no further discussion was done.

From the interview, the situation of on-site pileup was acceptable, but the inventory would be transferred to upper suppliers as per the contract. Therefore, a high inventory problem existed for raw material manufacturers and dealers, who would rather slow down production than stop production. If they really wanted to reach a zero inventory level, they would need time and a mindset change.

3.4. SCOR in the construction project application

After the case study, the research found that SCOR could efficiently help managers to build construction project supply chain models to understand the behavior of the supply chain members and measure the SCM performance. From the research, there were several findings about applying SCOR in construction projects:

SCOR provides a standard supply chain model applicable to different industries, but in construction, incompatibility exists when the 5 SCOR perspectives and sub-items are applied. In the definition of *Make*, customized products are often used to determine actual order specifications and sizes before starting production. As the aging properties of some building materials are unknown, this function cannot be fully implemented. In the *Delivery* process, some practices used in inspection and the process of returning purchased material or receiving returned product are run in *Deliver Make-to-Order* mode, therefore sub items in the five SCOR definitions appear simpler than for other industries.

The construction industry can use SCOR to measure the performance of all supply chains and compare them with competitors. The supply chain process was built based on SCOR to determine strategic factors for change, the related performance index, and define a new supply chain structure. After assessing the existing status, it was found that supply chain performance measures are reliable. If the performance measures lag far behind those from rivals, the company can take the *SCORCard* performance

measures as criteria for analyzing and improving supply chain management.

Construction business sources are unstable and manufacturers communicate information less efficiently, so not all SCOR reference models apply to the construction industry. The overall information concept has to be invested to execute SCOR properly.

SCOR introduction requires the coordination of all supply chain members. With the goal of improving the overall supply chain, information needs to be shared and communicated so as to enhance supply chain efficiency. SCOR is a process reference model, mainly used to build correlations governing all supply chain members. Similar to a kind of standard language, it allows managers to concentrate on management issues. Used as a company's standard operation procedure (SOP), SCOR can aid in cross-enterprise supply chain management and reserve much flexibility for various enterprise or project needs. The differences between using and not using SCOR are shown in Table 8.

In section 3.3. “Material inventory model optimization” and section 3.4. “Performance analysis of SCOR-based supply chain model of the case study”, the study found that without developing a dynamic supply chain model, the practitioners could only implement a trial and error method to find a better material procurement and inventory strategy. In addition, the requirements and usage of project materials changed with time. For example, the inventory level of the project materials changed during construction on the site. Thus, project managers should pay attention to the status of material usage and procure materials as necessary in order to meet the construction needs. Through dynamic modeling and material requirement planning, the optimal material management strategy can be obtained and the performance of the improved SCM can be identified. However, SCOR provides a static SCM model building standard. Dynamic simulation technology should be incorporated with SCOR to develop a dynamic model.

4. Conclusions and Suggestions

This study primarily investigated the supply chain behavior of a bridge construction project, from procurement and processing to field installation. It focused on key points of supply chain model design and analysis, and built a model using a dynamic simulation concept, in

order to aid practitioners in completing analyses of supply chain operation models. The conclusions of this study were as follows:

- i. This paper presented a supply chain design and behavior analysis method. Using a SCOR based dynamic model, the material management problems in the model can be identified. The practitioners can implement the proposed method to identify the best procurement alternative to improve the SCM of the target project.
- ii. Construction supply chains have huge structures covering many complicated industries, and no supply chain operation model has been built up to now. SCOR provides a supply chain operation model-building standard that can easily communicate among supply chain members, and offer a better understanding of their roles. A stakeholder in the supply chain can communicate directly with other members on improvement issues via the supply chain model.
- iii. SCOR provides a cross-industry supply chain model standard, but in construction, there is still incompatibility in the application of the five SCOR definitions and sub-items in the construction project. Construction products are vulnerable to non-determinable factors such as weather variations, and their process are somewhat different from common manufacturing processes, therefore not all SCOR operation models can apply to the construction industry.
- iv. SCOR presents a static SCM model building standard, however, construction supply chain behavior is a dynamic system changing with time, therefore it is necessary to build a dynamic system that can change with time and can adjust in response to demand and cost parameter changes, so that no conflict due to factor variations will occur. Thus, the study used dynamic simulation software to develop the construction supply chain model.
- v. SCORCard presents an SCM performance evaluation method, however, some data of the performance metric, for example *Target*, needs to be input manually. To solve this problem, the dynamic supply chain model presented can find the optimal procurement strategy solution via AI based intelligent solution searching methodology, which can be used as the SCM benchmark.

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PROCESŲ ANALIZĖ IR OPTIMIZACIJA STATYBINIŲ MEDŽIAGŲ TIEKIMO GRANDINĖJE**N.-H. Pan, M.-L. Lee, S.-Q. Chen**

Santrauka

Šiame darbe sistemingai analizuojami ir kuriami statybų tiekimo grandinės procesų modeliai. Remiantis etaloniniu tiekimo grandinės procesų modeliu, kurį sudarė Tiekimo grandinės taryba, nagrinėjama pasiūlos ir paklausos elgsena, atvejui tirti pasirinkus tilto perdangų statybos procesą. Naudojant SCOR modelį ir dinaminio modeliavimo programinę įrangą „SIMPROCESS“, darbe sudaromas hierarchinis modelis, leidžiantis nagrinėti procesų pobūdį statybų tiekimo grandinėse, ir sukuriamas veiklos efektyvumo vertinimo metodas, kuris gali padėti pagerinti statybų projekto tiekimo grandinės valdymą (TGV).

Reikšminiai žodžiai: etaloninis tiekimo grandinės procesų modelis, modeliavimas, statybų projektas.

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