Paper:

Development of Performance Simulation Model by Making Indices of Supply Chain Capabilities

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A supply chain (SC) is an organization in which multiple companies cooperate in supply functions, e.g., moving information or materials. Previous studies of SC designing and planning are categorized by their planning time periods into three categories, e.g., strategic, tactical, and operational. Top-down design of an SC, where design decisions are made in the sequence of strategic, tactical, and operational, is rational because of preventing rework of design work. But as few models supports strategic decision making quantitatively, top-down design of an SC has not been realized. In the present study, a method of quantitatively expressing SC's capabilities of flowing information and materials and simulating its performance is developed. The method is then implemented with a system dynamic model to evaluate, qualitatively and quantitatively, the effectiveness of the model.

1. Introduction

A supply chain (SC) is a system in which multiple companies cooperate in supply activities, e.g., moving information, materials, and money, in order to make a profit by responding to market demands. In general, an SC adapts itself to the environment and grows through a continuous improvement process. However, as a result of today's rapid change in the environment and accompanying difficulty in forecasting the future environment, SCs cannot adapt themselves sufficiently, which leads to problems such as supply failures, excess stock, and excess facilities. To solve these problems, dynamic redesign of SC is necessary [1] and the design should be an exante rational SC design, independent of self-organized growth, is necessary.

2. SC Design and Models for the Design

2.1. SC Decisions and Constraints

An SC is a process aiming to maximize cash flow (CF) by integrating various functions to flow information and materials. Ravindran [2] categorized decisions in terms of SC design into three hierarchies, namely, strategic decisions, tactical decisions, and operational decisions. Strategic decisions include design of SC network and facility capacities, decision of make or buy, choice of suppliers, ground design of IT system, and etc. Tactical decisions are about how to realize SC functions such as when and how much to purchase, when and how much to produce, and when and how much to hold inventories. Operational decisions are to schedule purchase, production, and delivery of specific materials.

Ravindran [2] points out that strategic decisions are subject to uncertainties but tactical decisions are less subject to it. This is because strategic decisions secure tactical decisions from uncertainties and tactical decisions are made based on strategic decisions. Thus, strategic decisions are constraints for making tactical decisions, and those are constraints for operational decisions.

2.2. Research Motivations

In considerations of constraint relationships of decision hierarchies, top-down design of an SC, where design decisions are made in the sequence of strategic, tactical, and operational, is rational because of preventing rework of design work and improving efficiency of design work. But Shapiro [3] pointed out there were few initiatives to move down the hierarchy to develop and use SC design models.

And as an SC integrates various functions to achieve maximizing CF, all functions consisting of functions of flowing information and functions of flowing materials should be designed comprehensively at a time. For instance, though production capacity is relatively small, big inventory capacity could enable the SC to respond peak demand quickly. Though inventory capacity is relatively

Table 1. Previous studies on SC design methods.

	Model Type							Performance Measures											Decision Variables by Decision Hierarchies and types — Strategic Decisions (Information flow)						Strategic Decisions (Material Flow)							Tactical Decisions (Information Flow)						Tactical Decisions (Material Flow)							Operational (Info Flow)	Operational (Material Flow)
Author(s)	Deterministic Anaylytical	Stochastic Analytical	Eeconomic	Simulation	Empirical model	Reference Model / Framework	Quality Function Deployment	Cost	Customer Responsiveness/Backorders	Financial performance	Marketing perfomance	CO2 emission	Activity Time	Flexibility	Agility	Inventory Level	Cash requirments	Facility/Labor utilization	Capabilities of flowing information	IT Alignment/Integration	Planning and execution capability	IT Advancement	Collaboration	Visibility	Supply Chain Configuration	Capabilities of flowing materials	Production Responsiveness	Agility	Logistics performance	Facility location	Supply Chain Network	IT System Diagram	Demand/Forecasting Information Sharing	Inventory Information Sharing	Production Information Sharing	Buyer - Supplier Relationships	Business Process Diagram	Number of Stage	Inventory levels/Ordering (Batch) Size	DC - Customer Assignment	Plant - Product Assignment	Product Differentiation Step Specification	Number of Product Types Held in Inventory	Production/Transportation Capacity	IT System Detailed Design	Production/Distribution Scheduling
[5] Al-Mashari and Zairi (2000)						X																																								
[6] Alendorfer et. Al. (2014)				X					X					X																															X	
[7] Altiok and Ranjan (1995)		X						X	X																														X	X						
[8] Arntzen, et. Al. (1995)	X							X						X																X									X		X	X				X
[9] Aviv (2001)	X							X																									X													
[10] Bottani (2009)				X											X																															
[11] Brusset (2016)			X												X				P						X																					
[12] Camm, et. Al. (1997)	X							X																						X										X						
[13] Chisty and Grout (1994)			X					X	X																										X											
[14] Choi and Fujioka (2006)					X			X																			X																			
[15] Cohen and Moon (1990)	X							X																																						X
[16] Georgiadis et. Al. (2005)				X																					X					X															X	
[17] Haq et. Al. (2006)			X					X						X																X			X													
[18] Harris et. Al. (2014)	X							X				X																		X																
[19] Huang et. Al. (2005)					X																																	X		X		X				
[20] Hwarng et. Al. (2005)				X				X	X							X																	X						X							
[21] Ishii, et. Al. (1998)	X							X	X																														X							X
[22] Kauremaa and Suzuki (2007)					X						X								P	X	X	X				P					X															
[23] Kubo (2001)	X																																													
[24] Lambert (2006)						X																			X					X									X							
[25] Lee and Billington (1993)		X						X																															X							
[26] Lee and Feitzinger (1995)		X						X																															X			X				
[27] Lee, et. Al. (1993)		X						X	X																														X							
[28] Lee, et. Al. (1997)		X						X																															X							
[29] Lowe et. Al. (2002)	X							X																	X	X															X				X	
[30] Lu (1995)																																														
[31] Nagurney (2010)	X							X																							X															
[32] Newhart, et. Al. (1993)	X							X	X																														X				X			
[33] Ovalle and Mauquez (2003)				X												X	X								X																					
[34] Ozbayrak and et. Al. (2007)				X				X								X									X																					
[35] Palaminos, P., et. Al. (2009)				X				X						X				X								P	X																			
[36] Pyke and Cohen (1993)		X						X																															X							
[37] Pyke and Cohen (1994)		X						X																															X							
[38] Schnessweis and Zimmer (2004)	X							X																														X	X						X	X
[39] SCOR (2008)				X																					X													X		X		X				
[40] Svoronos and Zipkin (1991)		X						X	X																														X							
[41] Towill (1991)				X				X	X																														X	X						
[42] Towill and Del Vecchio (1994)	X							X																															X							
[43] Towill, et. Al. (1992)				X				X	X										P				X										X	X					X	X						
[44] Tzafetas and Kapsiotis (1994)	X							X																															X							
[45] Vickery, et. Al. (1999)					X			X	X						X								X																							
[46] Vidal and Goetschalckx (2001)	X							X	X																					X										X		X			X	
[47] Voundouris (1996)	X													X																									X							X
[48] Wang and Wei (2007)				X											X				P	X			X																							
[49] Wikner, et. Al. (1991)				X				X	X																														X	X						
[50] Wu et. Al. (2006)				X							X	X							P	X		X												X												
[51] Yusuf et. Al. (2004)				X				X	X										P				X			P	X																			
[52] Zhang et. Al. (2007)				X				X								X																	X													
[53] Zhao et. Al. (2002)				X				X	X																									X												
This study				X				X								X	X		X	X						X																				

Legend) P:Partally considers the corresponding capabilities

small, IT system could adjust production schedule to meet sudden demand change.

The motivation of this study is to discuss the way to design the functions of flowing information and functions of flowing materials comprehensively at a time in the top-down approach.

2.3. Literature Review

Previous studies on the SC design modeling are surveyed and summarized in **Table 1** by adding studies after Shapiro's study [3] and studies on SC capabilities to Beamon's literature review [4], which summarizes model

type, performance measures, and decision variables, and by categorizing decision variables by decision hierarchies and flows of information or material.

Decision variables of many of the studies reviewed are tactical and operational. For instance, decision of batch size and number of stages are categorized to tactical ones and production and distribution scheduling are categorized to operational ones. In addition to strategic decisions such as SC network and facility capacities categorized by Ravindran [2], decision variables that are more abstract than tactical decisions, e.g., agility, visibility, and collaboration, are categorized to strategic decisions.

The reviewed studies whose decision variables are strategic adopt deterministic analytical models, simulation models, empirical models, reference models, and quality function deployment (QFD) as modeling methods. With adopting a deterministic analytical model, Camm et al. [12] modeled the effect of SC visibility on SC agility. With adopting a simulation model, Ovalle and Marquez [33] modeled the effect of information sharing among SC entities on inventory level and cash requirements of SC. Similarly, Ozbayrak and et al. [34] modeled the effect of collaboration among SC entities on inventory level and customer responsiveness of SC. The studies adopting empirical models are as follows. Kauremaa and Suzuki [22] modeled the effect of IT alignment and logistics performance on financial performance. Wang and Wei [48] modeled the effect of collaboration among SC entities on SC flexibility. Wu et al. [50] modeled the effect of IT alignment and IT advancement on financial and marketing performance of SC. Yusuf et al. [51] modeled the effect of collaboration on the cost and customer responsiveness of SC. By adopting a reference model, Choi and Fujioka [14] modeled the effect of production responsiveness on the customer responsiveness of SC and enabled to derive SC characteristics from its business environment. SCOR [39] is a set of reference models to derive SC configurations as strategic decisions and business process and IT system design as tactical decisions. By adopting QFD, Bottani [10] breaks down SC organizational culture to realize SC agility into consisting elements.

From the viewpoints of the study motivations, those studies whose decision variables are strategic are evaluated as follows. The studies adopting deterministic analytical models are modeling part of all functions of flowing information and materials such as SC visibility or information sharing among SC entities and do not handle all of them comprehensively. The studies adopting empirical models model the influences among performance measures and decision variables but do not decide decision variables. The studies adopting reference models and QFD neither decide decision variables.

In summary, no model supports making strategic decisions comprehensively and quantitatively that are basis for tactical and operational decisions while designing an SC in the top-down approach. Thus, top-down SC design has not been realized.
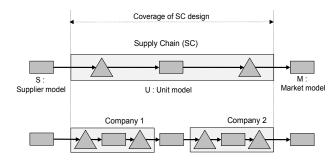

Fig. 1. Hierarchical structure and models.

2.4. Model for Top-Down SC Design

In order to model the SC strategic decisions, there are two approaches. One is to define decision variables of all the functions of flowing information and materials and model the effects on the SC performance measures. The other one is to abstract all the functions to reduce the number of decision variables and model the effects on the SC performance. As showed in Section 2.3, as decision variables of strategic decision are modeled only partially, the former approach is not realistic at this moment. In this study, the latter approach is adopted to discuss the challenges as below;

(1) To quantify levels of SC functions (capabilities) of flowing information and materials as few as possible.

(2) To simulate SC performance from SC capabilities.

This model is expected to enable top-down SC design, to decide SC capabilities in consideration of SC business environment and required SC performance, to make tactical decisions based on SC capabilities, and then to make operational decisions based on tactical ones.

3. Modeling of SC Constituents According to Capabilities

3.1. SC Element Models

S (Supplier) model, unit U (Unit) model, and market M (Market) model, shown in **Fig. 1**, are examined as elements expressing an SC. The unit model regards an SC as an organization and expresses information and material moving functions.

The supplier model expresses the supply of raw materials to the SC, and the market model expresses a change in demand to which the SC should respond.

One can expect that an SC composed of multiple companies would be expressed by regarding the unit model as a company and adding a link model that links companies. This study focuses only on the modeling of the SC as a single unit.

For simplicity, the following is presupposed. First, the money flow function is not taken into consideration. In addition, under the assumption that a major component per product determines the overall material flow in the SC,

Table 2. SC performance classification.

Index for sales amount and volume
Deadline meeting rate (Delivery deadline meeting rate)
Service level
Throughput
Delivery accuracy
Customer's satisfaction

Index for time of reaction to market change
Order fulfillment lead time (customer's reaction time)
Flexibility of supply
Upper elasiticity of supply
Batch size of production
Batch size of transportation
Down time of facilities

Index for operation rate of facilities
Operation rate of facilities
Fulfillment rate of storage
Loading rate

Index for inventory level
Inventory loss
Waste loss
Inventory turnover rate

Index for cycle time
Cycle time
Lead time from start of production to end
Plan cycle

Index for cost
Operation cost
Product cost
Inventory holding (management) cost
Inventory order placement cost
Delivery cost
Product returning cost

Index for cash cycle
CCC (Cash conversion cycle, cash-to-cash cycle time)
Number of inventory days
Number of days of receivable
Number of days of payable
Asset turnover rate
Space use rate
Investment profit rate

Index for product quality
Product quality

it is assumed that the market has a demand only for one product and that only one unit of raw material of only one kind is necessary to manufacture one unit of the product.

3.2. Selection of Performance Indices

To define the requirements for designing an SC and evaluating the design results, the SC performance index (Pi) is studied.

Since an SC has causality in that, if information and materials flow, then money flows as a result, a strategic SC design can be evaluated by actually developing and operating the SC and examining money flow, i.e., cash flow (CF).

Previous studies on the performance of SCs [54–59] were surveyed, and the items that represent the SC's performance were classified into 8 categories presented in **Table 2**. These indices are further arranged in **Fig. 2** as a causal loop diagram from the viewpoint of grouping and

CF maximization. Indices for sales amount and volume (1.), some of indices for time of reaction to market change (2.), and some indices for cycle time (5.) have positive correlations with cash flow through demand fulfillment rate and sales amount. Indices for operation rate for facilities (3.) have positive correlations with cash flow through operating rate of facilities and asset efficiency. Some of indices for time of reaction to market change (2.), indices for inventory level (4.), and one index for cycle time (5.), and one index for cash cycle (7.) have positive correlations with cash flow through inventory level and capital efficiency. As money flow function is not taken into consideration in this study for simplicity, indices for cost (6.) and some of indices of cash cycle (7.) are excluded. Index for product quality (8.) is also excluded.

Considering this figure, the following three Pi values are defined by taking into account the scale of the function design modeling in this study.

- Demand fulfillment rate: Product fulfillment rate for a given demand [%].

- Operating rate of facilities: Operating rate of bottleneck process [%].

- Low stock level: Average stock level over organization [pc].

3.3. Quantification of Material Flow Capabilities

SCOR [39] summarizes SC material flow functions by putting them into three categories: source, make, and deliver. In this study, the capabilities of these three functions are quantified to express the functions using as few elements as possible. In this quantification, three points that Toyota employs in its production are used: the "necessary amount" of "necessary materials" are delivered with the "necessary timing." These should be applied to other production methods criteria in the evaluation of material flow capabilities.

Under the assumption given in Section 3.1, the function of determining the "necessary timing" in the above is not necessary. One can also consider that the function of determining the "necessary amount" and "necessary timing" is included in the function of moving information, which will be explained below. Therefore, the function of moving materials can be evaluated in terms of the capacity and time of processing. In other words, the capability of moving materials could represent the maximum capability of the SC's physical facilities (constraint condition) and the capability of moving information could represent how much the facilities can be utilized.

The source function is represented by the maximum storage amount of sourcing inventory, i.e., how much processing can be done, and is called the "sourcing inventory capacity." The delivery function is represented by the maximum storage amount of delivery inventory and is called "delivery inventory capacity." The make function is represented by the maximum production amount per unit time and is called the "delivery inventory capacity."

Fig. 2. Performance grouping on causal loop diagram.

Fig. 3. Relation among material flow capabilities and Pi.

Since the functions of the SC work collaboratively to move materials, it is not necessary to define the lead-time of the processing, i.e., how the processing can be done in a short period of time, to all functions. For example, if the delivery function and the source function work collaboratively and if a lead-time is defined in the delivery function, it does not have to be defined in the source function.

Based on the above, the capability for moving materials in the unit model is defined as follows. The causal relationships between these capabilities and Pi are given in a causal loop diagram (**Fig. 3**).

- Source function: Sourcing inventory capacity [pc] (SI).

- Make function: Maximum processing capacity [pc/t] (MP).

- Lead time [t] (LT).

- Delivery function: Delivery inventory capacity [pc] (DI).

Fig. 4. Information flow capability.

Fig. 5. Relations among information flow capabilities and Pi.

3.4. Quantification of Information Flow Capabilities

The function of moving information is to determine the necessary amount and timing and to provide local sites with the plan to execute. To effectively make an operation plan, it is necessary to develop a bottleneck process plan first and then develop plans for the processes before and after it, making appropriate links between them [60]. Since processes presented by the unit model are production processes only, the level of the function of moving information is quantified in terms of the make function quantity and the precision of the timing determination and execution.
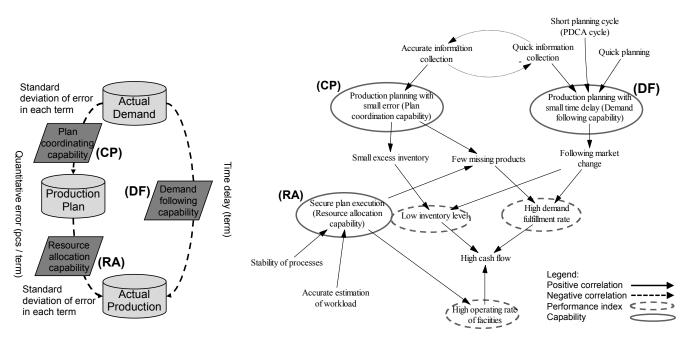
First, the necessary timing is determined from the delay time, or time from when an order is received to when production starts. In other words, demand follow-up capability is defined as the delay from when a production order is received and as the capability of moving information in order to move materials at the necessary timing.

Next, there are two ways of determining the necessary amount. One is to find the necessary amount in order to make a production plan, and the other is to direct and coordinate the making of products according to the production plan. The former capability is determined by the difference between actual demand, whose time deviation is corrected with the demand following time, and the created production plan, and it is called "plan coordinating capability."

In the latter, the capability is determined by the difference between the production plan and the production results, and it is called "resource allocation capability" (**Fig. 4**). For the production as planned, the appropriate allocation of related production resources is necessary. Based on these views, the unit model's capability of moving information is defined in the following way. Also, the causal relationship between these capabilities and Pi is shown in a causal loop diagram (**Fig. 5**).

- Planning function: Demand following capability [t] (DF).

- Planning function: Plan coordinating capability [pc/t] (CP: Plan Coordinating capability).

- Executing function: Resource allocation capability [pc/t] (RA: Resource Allocation capability).

3.5. Making a Model of Market and Supplier

Under the assumption given in Section 3.1, the market model is made in terms of product demand and the customer's allowed lead-time. To design an SC that responds to environmental changes, the market model needs to express environmental changes to which the SC should adapt itself. In order to express an environmental change as a numerical change in demand, the trend (the growth/decline of the market), periodic changes (e.g., seasonal changes in demand), and random changes (changes due to climate or customers' whims) are considered. The demand model is created as shown below.

- Demand amount [pc/t] (*D*: Demand) $D = a\sin(bt + c) + dt + e + norm(0, f)$.

- *a* [pc/t]: Amplitude of periodic change.

- *b* [degree/t]: Inverse of the period of the periodic change.

- *c* [degree]: Phase delay of the periodic change.

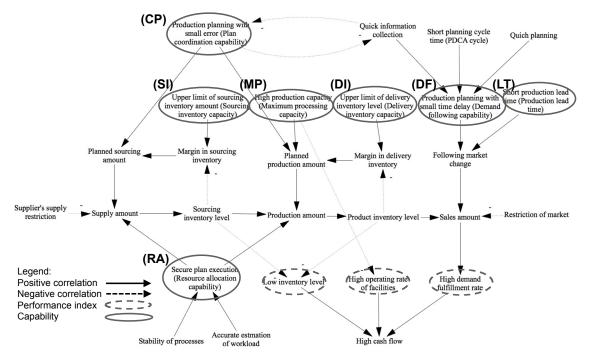- *d* [pc/t] (Trend): Increase/decrease in demand.

Fig. 6. Relations among capabilities and Pi via material flow.

- e [pc/t] (Average demand): Demand at $t = 0$.

- f [pc/t]: Standard deviation of random change.

- Allowed lead time [t]: (LT: Lead-Time)

The supplier is presented with the following parameters based on the unit model.

- Make function: Maximum processing capacity [pc/t] (MP: Maximum Processing capacity).

- Lead time [t] (LT: Lead Time).

- Plan function : Demand following capability [t] (DF: Demand Following capability).

- Plan function : Plan coordinating capability [pc/t] (CP: Plan Coordinating capability).

- Execution function: Resource allocation capability [pc/t] (RA: Resource Allocation capability).

4. Development of Simulation Model

4.1. Study of Modeling Method

The relation between the capabilities to flow materials and Pi in **Fig. 3** and that between the capabilities to flow information and Pi in **Fig. 5** are arranged and integrated into a single causal loop diagram (**Fig. 6**). By doing this, the relation between the material/information flow capability and Pi is simplified. For the development of a simulation model, there are three requirements for selecting a modeling method:

- Material flow can be expressed as time-dependent change.

- Relation between the capabilities via material flow can be expressed.

- Management mechanism of material flow can be expressed.

As modeling methods, discrete simulation, numerical model, and system dynamics (SD) were studied. Ashayeri pointed out discrete simulation requires many data for accurate modeling, and a numerical model is not suitable for expressing the time-dependent changes [61]. On the other hand, previous studies on SD modeling pointed out SD satisfies the above three requirements [16, 62–64]. Therefore, in the present study, the relation shown in **Fig. 6** is implemented with SD. Georgiadis et al. [16] also pointed out that SD methodology is suitable for modeling and analysis tools of supply chain where the life cycle of products are getting shorter and demand variability is getting larger. The SD software iThink (version 9.1.3, isee systems, inc.) is used.

SD is a modeling method that uses two modeling elements, namely stock and flow, to express a target and observe time-dependent changes. Stock represents the value of a variable at some point in time and flow represents the flow of the variable during unit time. In this study, the material flow is represented by "flow" and inventory by "stock." Operation information is represented by "converter," which indicates variables and information flow by "link," which indicates the causal relationship between the elements.
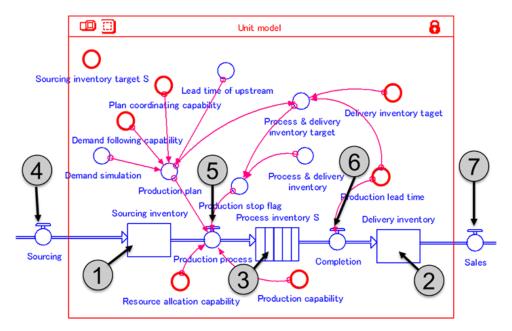
Fig. 7. Unit model expression by SD.

4.2. Idea of Modeling Based on Capabilities

The model describes how the SC's capabilities to flow information and materials would affect performance. The mechanism used to realize the capabilities is not taken into consideration because it is usually determined in the tactical design stage of the SC.

For example, in the present study, an SC's function of making an operation plan is included in the function of moving information. It is realized by the mechanism of feed forward, based on the demand forecast and on feedback information related to overstock or under-stock conditions that are caused by the execution of the operation plan. From a viewpoint of an SC's capabilities, the functions of its operation plan are evaluated in terms of time deviation (DF) and amount deviation (CP) between the actual demand and the production plan. Mechanisms such as feed forward and feedback are not described in the model.

4.3. Implementation of Unit Model with SD

As shown in **Fig. 7**, a unit model was implemented with SD. Stocks (① to ③) are connected with flows (④ to ⑦) and materials flow in the order ①, ②, ③, etc. The SC function modeled by each of them is shown in **Fig. 8**. Since the maximum number of materials stored in stock or lead time of the production cannot be set as parameters of the stocks in SD, the material flow is managed by controlling flows ④ to ⑦ in or from the stocks in the way described in **Fig. 7**.

- Stock ①, sourcing inventory: Maximum amount of stored products.

- Stock ②, delivery inventory: Maximum amount of stored products.

- Stock ③, production process: Lead time of production.

- Flow ④, sourcing: Products delivered from the upper organizations are sent to the stock "Sourcing inventory" (①) after being managed by the converter "Transport lead time."

- Flow ⑤, production process: When the converter "Production flag" is OFF, things of the amount indicated by the converter "Production plan" of each term is sent to the stock "Production process" but the amount should not exceed the converter "Production capability." The converter "Production stop flag" becomes ON, if the stock "Delivery inventory" exceeds the upper limit indicated by the converter "Delivery inventory target" when the stocks "Delivery inventory" and "Process inventory" are monitored.

- Flow ⑥, completion: Things flowing to the stock "Production process" are sent to the stock "Delivery inventory" after the time corresponding to the converter "Production lead time."

- Flow ⑦, sales: The converter "Market demand" and the stock "Delivery inventory" are compared with each other and the amount which corresponds the difference between them is sent from the stock "Delivery inventory."

4.4. SD's Expression of Performance and Influence

When the information and material flows are modeled in this way with the SD, it is necessary to find how the capabilities of moving information and materials are expressed and what they affect.
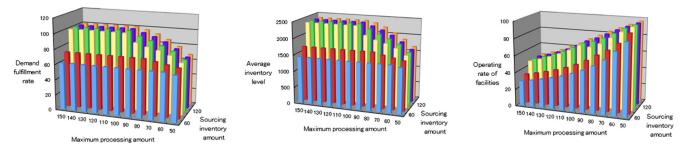
Fig. 8. Effects of Pi on DF (demand following capability) and DI (delivery inventory capacity).

SI (sourcing inventory capacity) of the capability of moving materials is set to the converter "sourcing inventory target." With high SI, the amount of production can be increased quickly, even if there is a sudden change in demand. MP (maximum processing capacity) is set to the converter "production capability." With high MP, materials can be supplied quickly, even if there is insufficient delivery inventory for sudden changes in demand. LT (lead time) is set to the converter "production lead time." With a small LT (short lead time), materials can be supplied quickly even if there is insufficient delivery inventory to handle a sudden change in demand. DI (delivery inventory capacity) is set to the converter "delivery inventory target." With high DI, production can be increased quickly if there is a sudden change in demand. All of these could help to increase sales and the rate of demand fulfillment.

DF (demand following capability) is set to the converter "demand following capability." It expresses the lag time between a demand change in the market and a production plan process. With a small DF, an SC's constituent companies can quickly transfer the market demand to the upstream companies. PC (plan coordinating capability) is set to the converter "plan coordinating capability." It expresses quantitative errors in the production plan process from the demand change in the market. These quantitative errors are mostly the ones in the demand forecast. RA (resource allocation capability) is set to the converter "resource allocation capability." It expresses errors in the execution of the production plan. These errors mainly represent the stability of the production process or certainty of the sourcing.

4.5. Qualitative Study of Unit Model Behavior

Using the unit model, we examined whether the SD model could reproduce the relations among an SC's seven capabilities and three Pis (**Fig. 8**). Since a single capability could affect multiple Pis and a single Pi could be affected by multiple capabilities, the relation between two capabilities and each of the Pis is shown in the following graphs.

For example, as for the relations among a Pi, DF (demand following capability), and DI (delivery inventory capacity), market model parameters ($a = 30$, $b = 1$, $c = 0$, $d = 0$, $e = 70$, $f = 0$), supplier model parameters (MP =
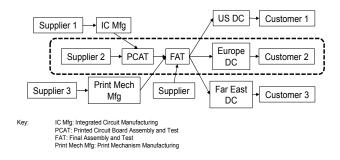

Fig. 9. Supply chain of HP [65].

100, LT $= 0$, DF $= 0$, PC $= 0$, RA $= 0$), and unit model parameters (MP $= 100$, LT $= 0$, SI $= 100$, PC $= 0$, RA $= 0$) were set. The unit model's DI was changed from 150 to 350 by 50, and its DF was changed from 0 to 60 by 10.

The left graph in **Fig. 8** shows the effect on the Pi demand fulfillment rate. When DF (demand following capability) decreases from the maximum value 0, the Pi demand fulfillment rate decreases. Also, even when DF (demand following capability) is 0, the Pi demand fulfillment rate decreases if DI (delivery inventory capacity) is lower than 250.

The central graph shows the effect on the Pi average stock, and the right graph shows the effect on the Pi facility operating rate. Also, the relation of MP (maximum processing capacity) and DI (delivery inventory capacity) to Pi and that of MP (maximum processing capacity) and SI (sourcing inventory capacity) to Pi were analyzed in the same way, and it was confirmed that the unit model works as intended.

5. Quantitative Study of Capability Model

5.1. Study Method

The accuracy of the capability model with SD is to be examined with the following 3 steps; Step 1: to measure performance and capabilities of the study target SC, Step 2: to reproduce the study target SC by capability model, Step 3: to simulate performance of the study target SC by capability model and compare with the performance of the study target SC.
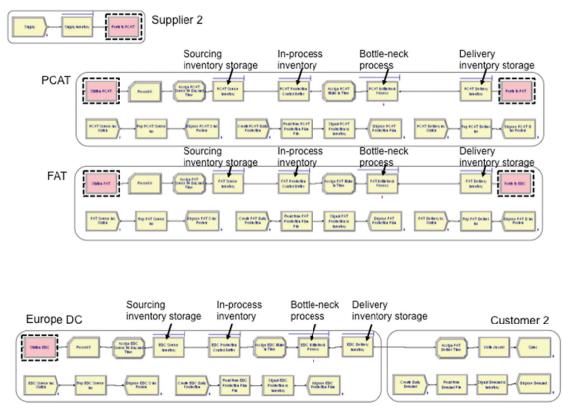
Fig. 10. Study target SC simulated with ARENA.

5.2. Study Target SC

As study target SC, we chose the HP printer production supply chain (**Fig. 9**), which was analyzed in a previous case study [22]. Instead of being collected from the actual SC, information that was missing in the case study was added arbitrarily. Then an SC was developed on the discrete simulation (ARENA, Version 13.00.00 (CPR 9 SR 1), Rockwell Automation Technologies, Inc.).

In **Fig. 9**, the area circled in dotted line, including Supplier 2, PCAT process, FAT process, Europe DC, and Customer 2, is chosen as study target SC. A discrete simulation model developed with ARENA for this area is shown in **Fig. 10**. The organizations of Supplier 2, PCAT process, FAT process, Europe DC, and Customer 2 are given from top to bottom in **Fig. 10**. Each organization contains modeling elements in two rows. The upper row shows the material flow: the lower shows the flow of information, such as the demand and production plan.

The square with dotted line at the end of each organization presents the operation of delivery and receipt, and the other squares show production processes and inventory spaces. Along the material flow in each organization, there are four squares: sourcing inventory storage, in-process inventory, bottleneck process, and delivery inventory storage, from left to right. For the bottleneck process, the maximum processing capacity per unit time and the time required for the processing are set. For the sourcing inventory storage and delivery inventory storage, the maximum inventories are set. The in-process inventory

corresponds to a production process before the bottleneck process, and a certain amount of inventory in this production process could smoothly supply parts to the bottleneck process. It is assumed that the suppliers and transport companies have no operation plans, and delivery or transport is made upon the receipt of requests from the downstream organizations. With this premise, the parameters of each modeling element are set, as shown in **Fig. 10**.

In this discrete simulation, the operation of the target SC is reproduced by giving demand information, production plans for PCAT and FAT processes, and a delivery plan for Europe DC. The demand information for 1,000 days is computer generated by assuming a daily demand change pattern for each month based on actual monthly demand of the SC over the course of three years. The production and delivery plans with some time delay and quantitative errors are computer generated by assuming that the propagation of the demand information takes time and that accurate demand influence cannot be obtained.

5.3. Step 1: Measurement of Performance and Capabilities of the Study Target SC

The operation of the target SC under study was reproduced by implementing demand information, production, and a delivery plan created in this way in the discrete simulation model shown in **Fig. 10**. The operation of this SC was evaluated in terms of Pi values: demand fulfillment rate = 72.8%, low inventory level = 575 [1,000 pcs], and operating rate of facilities = 31.4%.
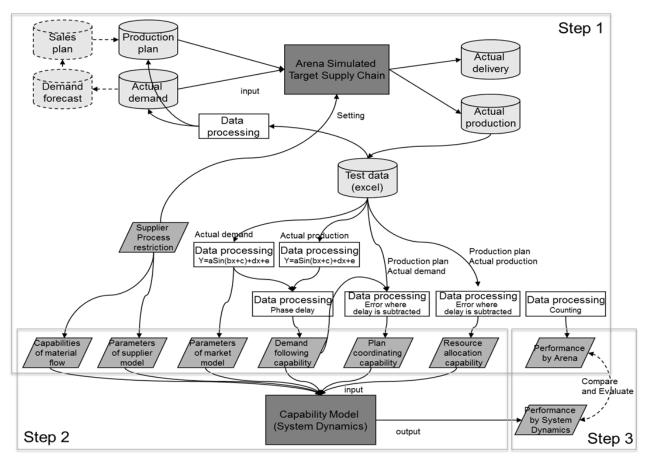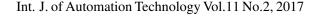
Fig. 11. Study steps and program for calculating information flow capabilities.

5.4. Step 2: Reproduction of Study Target SC by Capability Model

In order to express the SC with a capability model, it is necessary to divide the entire SC into processes, sourcing inventory, and delivery inventory.

In this SC, product inventory is made by make-to-stock manufacturing, stored in the Europe DC, and shipped upon order. Therefore the inventory in the Europe DC is regarded as the SC's delivery inventory. Since the bottleneck process determines the production speed of the entire SC, the processing amount of the FAT process, which is the bottleneck process of the SC, is regarded as the SC's maximum processing capacity (MP). Also, the time from when materials come to the FAT process to when the SC is ready to deliver products is regarded as lead-time (LT). The inventory from the start of the FAT process to the start of the delivery inventory is regarded as process inventory, and the inventory in the upstream side of the FAT process is all regarded as sourcing inventory.

Based on the idea in **Fig. 4**, the capabilities to flow information was determined by providing the processing program, shown in **Fig. 11**, with the production plan given to the FAT process and the demand and production results obtained from the discrete simulation. The parameters of the supplier and market model were also determined using this processing program shown in **Fig. 11**.

Fig. 12. Measured parameters of supplier/unit/market models.

5.5. Step 3: Simulation of Performance by Capability Model

Using the market model, unit model, and supplier model parameters (**Fig. 12**) specified in the above, we developed a capability model with SD and made simulations. The Pi values were demand fulfillment rate = 77.1%, low inventory level = 799.5 [1,000 pcs], and operating rate of facilities = 32.0%. The Pi values of the target SC and the capability model are compared in **Table 3**.

Table 3. Comparison of Pi values.

	Pi value		
	Demand fulfillment rate	Low inventory level	Operating rate of facilities
Study target SC	72.8%	575.0	31.4%
Capability model	77.1%	779.5	32.0%
Difference	5.6%	26.2%	1.9%

6. Summary

6.1. Conclusions

The difference in the Pi value of the demand fulfillment rate between the SC and the capability model was +5.6%, and that in the Pi value of the facility operating rate was +1.9%. These differences are sufficiently small in this first stage of the function design. In other words, by implementing with the capability model the study requirement of (1) to quantify levels of SC functions (capabilities) of flowing information and materials as few as possible, (2) to simulate SC performance from SC capabilities, in Section 2.4, we have verified the usefulness of the model.

This outcome means that seven capabilities can represent levels of SC functions of flowing information and materials with reasonable accuracy. With this capability model of SC, top-down SC design, to decide SC capabilities in consideration of SC business environment and required SC performance, to make tactical decisions to realize functions, and then to plan operation schedules, will be enabled.

6.2. Remaining Problems

On the other hand, the Pi of the low inventory level is as large as +26.2%. This should be due to the difference in the operation occurrence frequency between the discrete simulation study target SC and the capability model with SD. In the discrete simulation, materials are produced and transported every time materials arrive, while they are made once a day in the SD model. As a result, the target SC handles smaller lots of materials for production and transport and has a lower inventory level. It is therefore necessary to identify this difference in advance and take it into account in the simulation of performance.

Also, in order to apply this capability model to top-down SC design, the following models or methodologies are necessary to be discussed;

(1) To optimize or decide the seven capabilities of an SC to realize required performance.

(2) To distribute an SC's capabilities to flow information and materials to constituent entities of the SC.

(3) To define steps to take in making top-down design of an SC by using the above models.

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