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Modeling of Supply Chain Contextual-Load Model for Instability Analysis

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1. Introduction

Simulation provides an alternative method for detailed analysis of the complex real world systems such as the supply chain. Given that a simulation model is well-suited for evaluating dynamic decision rules under 'what-if' scenarios, a few attempts have been made to develop simulation models to improve supply chain performances. The modelling of supply chains dynamics adopted to simulation approach has been reported by many authors including (Towill *et. al.*, 1992), (Badri, 1999), (Bhaskaran, 1998), and (Sadeh *et. al.*, 1999).

More specifically, (Towill *et. al.*, 1992) used influence diagrams to visualise the cause-and-effect relationship between the decision rule and the improvement of supply chain performances. The main purpose of the study is to create a best decision rule that will allow the decision maker to reduce lead times, compress the distribution channel and co-ordinate information flow throughout the supply chain. (Bhaskaran, 1998) conducted a simulation analysis of supply chain instability. He shows how supply chains can be analysed for continuous improvement using simulation. The focus is on a stamping pipeline in an automobile supply chain based on operating data from General Motors. (Badri, 1999) developed a simulation-based decision-support system for multi-product inventory control management to enhance the competitive advantage of a furniture manufacturing firm using the simulation language SLAMSYSTEM and some statistical models. He claimed that the model allows managers to examine different inventory systems and policies without resorting to unrealistic assumptions and methods or having to use complicated mathematical techniques. (Sadeh *et.al.*, 1999) proposed an architecture that aims at providing a framework for coordinated development and manipulation of planning and scheduling solutions at multiple levels of abstraction across the supply chain. The architecture is configured around a blackboard architecture to allow for the easy integration of multiple planning and scheduling modules along with analysis and coordination modules.

Source: Supply Chain, Theory and Applications, Book edited by: Vedran Kordic, ISBN 978-3-902613-22-6, pp. 558, February 2008, I-Tech Education and Publishing, Vienna, Austria

Discrete-event systems (DES) simulation models are also a very popular approach for these types of problems. This simulation approach allows different combinations of decision strategies to be evaluated and thus provide adaptivity necessary for efficient use in dynamic, on-line environments. Compared with the previous DES tools for example GPSS, and SIMAN etc., the many sophisticated DES simulation packages available today, able to provide a more detailed simulation capability, even for real-time planning, scheduling and control, examples are ARENA, Witness, etc. (Terzi & Cavalieri, 2004) provide a comprehensive survey on over 80 simulation studies, how discrete-event simulation techniques could represent one of the main IT enablers in a supply chain context for creating a collaborative environment among logistics tiers. They establish which general objectives simulation is generally called to solve, which paradigms and simulation tools are more suitable, and deriving useful prescriptions both for practitioners and researchers on its applicability in decision-making within the supply chain context. The discrete-event simulation can be identified under two structural paradigms: local simulation paradigm, i.e., using only one simulation model, executed over a single computer, see for example, (Ingalls *et al.*, 1999), (Jain *et al.*, 2001) and (Lou *et al.*, 2001) and parallel and distributed simulation paradigm, i.e., implementing more models, executed over more calculation processes using computers and/or multi-processors, see for example, (Gan & McGinnis, 2001), (Brun *et al.*, 2002) and (Zulch *et al.*, 2002). The methods to explore supply chain strategic decision support, production planning and distribution resources allocation, multi-inventory planning, and distribution and transportation planning have been reported for example in (Bottler *et al.*, 1998), (Schunk, 2000), Promodel (Supply Chain Guru, 2002), and (Bagchi *et al.*, 1998), respectively. However, the efforts of developing tools for decision support of adaptability to disturbances in supply chains are still lacking.

This work aims to answer a key question: what will be the dynamic behaviour of a particular parameter (example, the inventory level) in response to a change of a disturbance parameter value (example delay in delivery) at a different location in the system? The focus will be to study the effectiveness of the controller (decision policies) to provide stability under the presence of disturbances, as well as evaluating the effect of disturbances on the process (the supply chain system), and this is achieved via DES simulation.

There are various situations that could be addressed, but in this work, some of the questions to which answered are sought, are as follows:

- Will the system be able to adjust to *changes in product demand*?
- For example in situations where the lower echelon reduces orders, or increases orders.
- Will the system be able to adjust to changes in *manufacturing capacity*?
- For example in situations of machine breakdown.
- Will the system be able to adjust to *inventory disturbances*?

For example in situations where supplier provides incorrect amount of material.

Accordingly, the answer to this issue can be addressed through contextual load modeling. Meaningful analysis for revealing the complex behaviour of the supply chain system must consider modeling the system and its relation to its contextual components, that is, how the supply chain system would react to its environment. Such a model can be viewed as consisting of the supply chain model, made up of several components, together with its contextual components. These components are dynamic and are characterised by several variables, each changing with events and each linked through events to other variables.

Each of the particular situations of interest represents one contextual component of the complex system (the supply chain).

It is worth pointing out the difference between our method and other simulation models. Most of these methods, see (Badri, 1999), (Sadeh *et. al.*, 1999), and (Towill *et. al.*, Naim and (Wilkner, 1992), concentrate on issues like creating the best decision rule, but do not consider the complex relationships that occur if an upstream echelon fails to serve a downstream echelon. Ours, in common with for example (Bhaskaran, 1998), is focussing on analysing the supply chain instability. However, our approach allows detailed experimental set-up for example evaluating the effect of disturbances on the process (supply chain system) and addressing issues whether decision policies would provide stability in the presence of disturbances, see (Saad, 2003).

The chapter is organised as follows: section 2 discusses the supply chain system, and the inventory control policies researched. Section 3 summarises the design and development of the supply chain contextual load model, and describes the test model and procedures used. Illustrative examples demonstrating the applicability of the approach is presented in section 4. Section 5 gives the conclusions of this chapter.

2. The supply chain model description

A packaging industry supply chain description to be modeled via the contextual load modeling approach is given in this section.

The following main notation will be applied:

Notation	Description
x	Subscript indicating company $x=\{A B C D E\}$
ss	Subscript indicating steady state condition (example, $u_{Ess}(d)$)
i	Day of the week index ($i=0$ indicates Sunday), $i=0, \dots, 6$
w	Week number index, $w= 0, 1, \dots, W$
d	Day number index (numbering starts from start of simulation) $d=(7w+i)$ or, $d=0, 1, \dots, D$
e	Size of emergency order sent to printer
$I_x(d)$	Inventory level of printed labels at company x on day d
$p_x(d)$	Production at company x on day d
S_x	Order-up-to-level for company x
s_x	Re-order level for company x
ss_x	Minimum stock level for company x
$u_x(d)$	Order placed by company x on day d
$V_D(w)$	Average variation in weekly orders placed by company D measured at week w
$y_x(d)$	Goods delivered by company x on day d

Table 1 The main notation

Additional notation will be introduced as the need arises.

Figure 1 is a schematic diagram illustrating the relationship between the companies in the chain, the end product of which is the supply of boxes of fresh vegetables to a retailer.

Company A, the raw material supplier, supplies both paper and laminate to company B who produces rolls of blank labels. It is assumed that the adhesive is always available. Company B, the blank labels supplier, produces rolls of sticky labels (in customized sizes) from larger rolls of paper and adhesive. The blank substrate is supplied to company C, the label printer, who print, cut and supply label rolls to company D, the packer/filler. Company D is a large co-operative fresh produce company who, in addition to growing their own produce, purchase from a number of market gardeners and overseas companies. Company D packs and labels the product and supplies it to the distribution centre for company E, the retailer. Company E on receiving the ordering information from their stores will initiate the demand for boxes of fresh vegetables, and provides this information to company D.

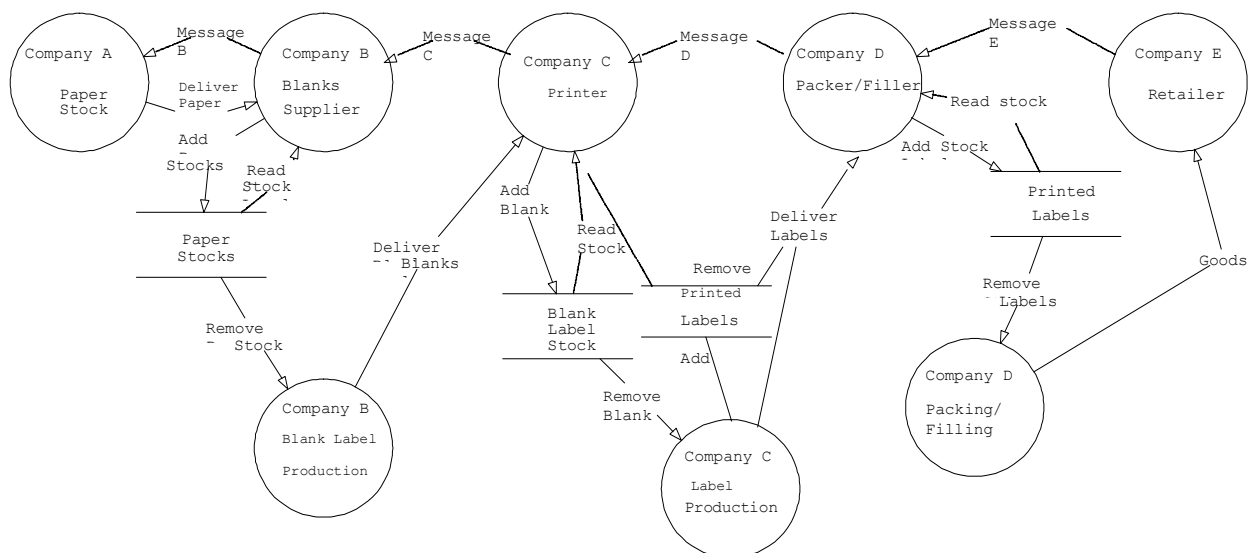


Figure 1. A schematic diagram of the packaging industry supply chain.

2.1 The model description

At steady state, assuming order from retailer (E) to packer/filler (D) equal $u_E(d)$. Packer/filler (D) uses a *generic policy* as the inventory policy to generate the orders. Minimum stock level for deterministic demand (safety stock level) at packer/filler equal ss_D . Re-order level at packer/filler $s_D = ss_D + LT \times u_E(d)$ units/day, where LT is the lead time equal three days. A weekly order from packer/filler (D) to printer (C) equal $u_D(d)$, and the order is sent on day, $i = 0$, that is Sunday. In addition to the weekly Sunday order, an emergency order, e , is sent if the stock level plus the quantity on order, falls to or below a threshold re-order level, $s_{D \text{ threshold}}$.

This is expressed via the following inequality:

$$I_D(d) + \sum_{i=0}^d [y_C(i) - u_D(i)] \leq s_{D \text{ threshold}} \quad (1)$$

where $s_{D \text{ threshold}} = (s_D - (ss_D - u_E(d)))$

The emergency order, $e = 7 * u_E(w+i) - I_D(7w+i)$.

Printer company (C) can produce 100 units per hour and operates one shift of eight hours each day, i.e., maximum capacity of printer production equal 800 units. The delivery delay between printer (C) to packer/filler (D) is three days. It uses (s,S) policy for ordering blanks from blanks supplier. This inventory policy is very common in practice, see Silver & Peterson (1985). Order from printer (C) to blanks supplier (B) is sent if stock level plus quantity on order falls below s_C , units of blanks. In addition to the blank labels stock, there is also a buffer (intermediate) stock of printed labels in company C to hold some stock of printed labels. The quantity is typically between 100 and 200 units. The inventory policy is that sufficient labels are held in stock to meet needs of a sudden increase in order from packer/filler (D). The control decision is as follows: If buffer stock falls to or below 100 units, print $p_C(d)=y_D(d)+100$ units and add 100 units to buffer stock. If buffer stock is above or equal 200 units, print $p_C(d)=y_D(d)-100$ units and take 100 units from buffer stock. Blanks supplier uses (s,S) policy for ordering paper and substrates from raw material supplier. Order from blanks supplier (B) to raw material supplier (A) is sent if stock level plus quantity on order falls below s_B , units of blanks. Company A is assumed be able to provide a continuous supply of raw materials to company B.

2.2 Inventory control policies

The policies have been formulated based on observation of real-life process and also based on systems principles. The packer/filler company has access to information like the retailer's order, and the stock level at the packer/filler inventory. The packer/filler makes its own decision on how much to order by generating the order quantity based on the decision policy. The order generated by the retailer is issued directly to the packer/filler. No changes were made to the decision policies implemented at the printer company and the blanks supplier company.

The description of each policy at the packer/filler (D) is as follows:

a. Generic policy :

This policy is expressed heuristically as follows: A weekly order is placed with the order quantity equal to a weekly supply, or a seven day supply to retailer. An emergency order is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point. The order quantity equals the difference between a weekly demand and the current stock. A closer look at this policy would suggest that it may be identified as the hybrid of the fixed size periodic review (fixed size of weekly order) and the continuous review (variable size of emergency order). The reviewing period is always scheduled for a particular day of the week as well as can be made at practically any day of the week. Detailed discussion on the periodic and the continuous reviews can be found in Hariga & Ben-Daya (1999) and Naddor (1966).

b. (s,S) policy:

This policy dictates that an order be placed when the stock declines to a lower control limit called the order point, s . The order quantity is the amount necessary to bring the inventory level to the order level, S . The (s,S) policy assumes continuous review. An emergency order is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point. A more detailed discussion on the (s,S) policy can be found in (Silver *et. al.*,1998).

c. Pseudo PID policy:

The thrust of the idea for proposing this policy in this work comes from the control system representation and the use of feedback. Feedback has often had revolutionary consequences with drastic improvements in performance, see (Bennett, 1993). The PID controller is by far the most dominating form of feedback in use today and is used in wide range of problems, see (Astrom & Hagglund, 2001). An analogy to inventory control would be in the design of a controller that keeps process variables within range: a typical situation for level control in surge tanks where it is desired that the level changes but it is not permitted either to have the tanks flooded or to have them empty. Such use of PID type policy for inventory control is new and not available in the literature.

The operation of the pseudo PID policy is summarised as follows: An order is placed when the stock declines to a lower control limit, s , as described in the equations as given below. k_p , k_i , and k_d represent the proportional, integral, and derivative gains, respectively. The actual order is obtained from its desired value, after taking the physical limits of the inventory system and its dynamics. An emergency order, e , is placed on any day of the week if the stock plus the quantity on order declines to a lower limit called the re-order threshold point. As with the PID controller to improve steady-state error, the value of the order is adjusted accordingly using the expression representing the controller action.

The policies description given above are translated into their corresponding mathematical equations. The respective mathematical equations of the corresponding policies are as follows:

a. Generic

$$u_d(7w+i) = \begin{cases} 7u_e(7w+i), & i=0 \\ e, & i \neq 0 \end{cases} \quad (2)$$

b. (s,S)

$$u_d(7w+i) = \begin{cases} 7^*u_e(7w+i) + [s_D - I_D(7w+i)], & i=0 \\ e, & i \neq 0 \end{cases} \quad (3)$$

c. Pseudo PID

$$u_d(7w+i) = \begin{cases} k_p * 7u_e(7w+i) + k_i \sum_{j=1}^n [s_D - I_D(7w+i+j)] + k_d [u_e(7w+i) - u_e(7w+i-1)], & i=0 \\ e, & i \neq 0 \end{cases} \quad (4)$$

In the above, the value of e is computed, with $s_{D \text{ threshold}} = (S_D - (ss_D - u_E(d)))$, as follows:

a. Generic policy

$$e = \begin{cases} 7u_e(7w+i) - I_D(7w+i), & \text{if } I_D(d) \leq s_{D \text{ threshold}} + \sum_{i=0}^d [u_D(i) - y_C(i)] \\ 0, & \text{if } I_D(d) > s_{D \text{ threshold}} \end{cases} \quad (5)$$

b. (s,S) policy

$$e = \begin{cases} 7u_e(7w+i) + ss_D - I_D(7w+i), & \text{if } I_D(d) \leq s_{D \text{ threshold}} + \sum_{i=0}^d [u_D(i) - y_C(i)] \\ 0, & \text{if } I_D(d) > s_{D \text{ threshold}} \end{cases} \quad (6)$$

c. Pseudo PID policy

$$e = \begin{cases} 7u_E(7w+i) - I_D(7w+i), & \text{if } I_D(d) \leq s_{D \text{ threshold}} + \sum_{i=0}^d [u_D(i) - y_C(i)] \\ 0, & \text{if } I_D(d) > s_{D \text{ threshold}} \end{cases} \quad (7)$$

The main purpose of these policies is to act as a controller to countermeasure the disturbance due to fluctuations in the daily orders from retailer. The aim is to have a controller (decision policy) that keeps the process variable, that is, the inventory level within range. Basically, it is desirable that the inventory level changes but that it is not permitted to exceed a maximum level or be empty.

3. Contextual load model design

The contextual load modeling is conducted in this work with the realisation that meaningful investigation of a particular system, in this case the supply chain system, can be achieved by explicitly accounting for its environment. The task of developing the contextual load model would require the identification of the possible sources of disturbances that might exist in the system, the modeling of these disturbances and to decide the particular parameters in the model that is to be changed to simulate such disturbances. With this view, it is necessary to develop a general conceptual framework towards implementing a systematic and efficient representation of the contextual load model.

In this general conceptual framework, the orders (messages) can be regarded as feedback signals. The inventory (stock levels) is regarded as the controlled variable, CV. The measured value of the CV is transmitted to the feedback controller (decision-maker), and this controller makes a decision on the quantity to order or to be issued to the upper stage (echelon) based on the ordering policy (rules). The feedback controller (decision-maker) calculates the required amount to order based on the stock level, PV, and the ordering policy (rules). This value is reflected as the needed values of the manipulated variables, MV. The process represents the physical changes of the entities, for example, the process of transforming blank labels into printed labels, etc. Disturbance is any undesired change that takes place in a process which tends to affect adversely the values of the CVs, the input or the process.

On receiving an order from the lower echelon (retailer), the decision-maker at the packer/filler company will decide on when to start production, and at a specific time of the day will issue this information, as a MV (shows as MV_D) to the packer/filler production. Also, at some specified time of the day, the printed labels stock level is read. This information is used by the decision maker at the packer/filler company to decide on the size to order, the time to place an order, and perform the ordering. This is shown as u_D , or PV_C . This information is later used to calculate the required MV_C . Hence, the decision-maker at the packer/filler company is analogous to a feedback controller that performs the control of issuing orders and production, and regulates the stock level.

The same analogy also applies to the decision maker at the printer company. On receiving an order, u_D , from the lower echelon (packer/filler), the decision maker at the printer company will decide on when to start production, and at a specific time of the day will issue this information, as a MV (shows as MV_C) to the printer production. Also, at some point in time, the blanks labels stock level is read. This information together with the information

from the printed labels stock (company C) is later used to calculate the required u_C or PV_B . This information is then used by the decision maker at the blanks supplier (upper echelon), to calculate the required MV_B .

3.1 The sources of disturbances

Disturbance is any unwanted signal that corrupts the input and output of the plant or the process. The control system structure as depicted Figure 2 shows a detailed description of the system, including the disturbances.

The diagram of the system as depicted in Figure 2 underlies the identification of the disturbance types that may be present, namely: (a) The set-point (input) disturbance - designated as Type I disturbance, (b) The process (plant) disturbance - designated as Type II disturbance, and (c) The control variable (output) disturbance - designated as Type III disturbance. This selection correlates with the concepts from control system theory.

Table 2 summarises the disturbance types and their possible sources to be considered in the modelling of the contextual load model. As shown, the disturbances could have originated from a change in product demand (or variations of orders from retailer) - a Type I disturbance, change in manufacturing capacity - a Type II disturbance, and also disturbance to inventories - a Type III disturbance.

In this study, a changing operating point, and customer cancelling orders are two of the examples for Type I disturbance. An example for Type II disturbance is in the event when machine breakdown occurs, while examples for Type III disturbance includes stock wastage, faulty materials, late delivery, and supplier providing incorrect material.

Type	Disturbance	Sources of disturbances
I	Change in product demand	Changing operating points Customer cancel orders
II	Manufacturing capacity	Machine breakdown
III	Inventory disturbance	Stock wastage Faulty materials Late delivery Supplier providing incorrect material.

Table 2. Disturbances type and the sources of disturbances.

3.2 Modeling the disturbances

The objective of this work are to assess the effectiveness of each ordering policy in adjusting to changes in product demand, changes in manufacturing capacity, and inventory disturbances. The next task in developing a contextual model would require an understanding on how to model these disturbances and to decide on what particular parameter(s) in the model to be changed to simulate such a particular disturbance.

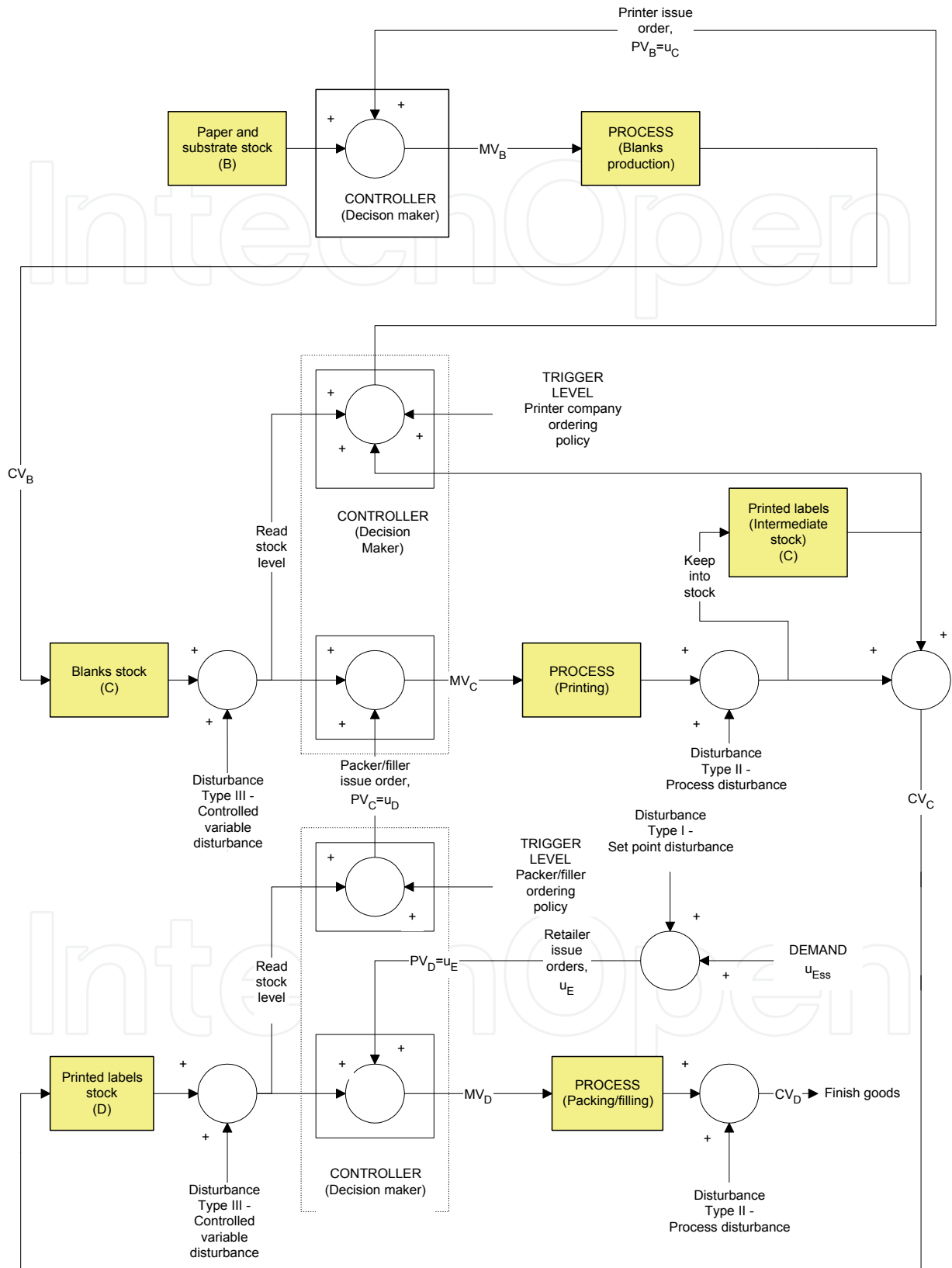


Figure 2. The control system structure of the packaging industry supply chain system

3.2.1 Type I disturbance: change in product demands

- *Changing in operating points:*

A variation in ordering pattern from the retailer will represent changes in product demands. For example, modelling this disturbance on the packer/filler company requires the model components to simulate an occasional change in the order quantity of retailer deviating from that of the usual demand due to product promotions and/or seasonal and trend factors.

- *Customer cancelling orders:*

The modeling of a cancellation of order is achieved by making the order quantity from retailer to drop to zero for that particular day.

3.2.2 Type II disturbance: manufacturing capacity disturbance

- *Machine breakdown at printer:*

Breakdowns can have a major effect on the performance of manufacturing systems. Many authors have discussed the proper modelling of breakdown (or downtime) data. These have been extensively discussed in Banks (1996), Williams (1994), Clark (1994), Law and Kelton (1991). Breakdowns can be deterministic or probabilistic in duration. Scheduled maintenance can be classified as deterministic. The breakdown is classified as probabilistic for almost all other circumstances. However, this requires either actual data for choosing a statistical distribution, or a reasonable assumption when data is lacking based on the physical nature of causes of downtimes.

In this study, two cases will be considered: (a) breakdown occurs before a regular order was made, and (b) breakdown occurs after a regular order was made. The following assumption is made regarding its implementation: failure is modelled to take place immediately upon the occurrence of a breakdown. Once the machine has been repaired it will continue processing the order that was interrupted when breakdown occurred, until completion. Any order that was received during the breakdown period will not be processed.

- *Faulty materials in printer:*

It is assumed that some portions of the material are damaged during the printing processes. This disturbance is modeled by treating that when packer/filler (company D) make an order of q units, the printer (company C) will print the amount as ordered. The production at printer will be q units, but due to faulty material the quantity delivered to packer/filler will be q units less the faulty.

- *Late delivery:*

This disturbance arises due to an unnecessary delay in the delivery of goods from printer company to packer/filler company. For example, late delivery may happen a few times during a certain period of time. The modeling of this disturbance is achieved by using a pure time delay block between the printer and the packer/filler.

- *Stock wastage in packer/filler:*

It is assumed that there are some percentage of material being damaged during transportation, or that material is scrapped due to changes in design format. In terms of disturbances, this would be reflected as an inventory disturbance, whose modelling has been discussed earlier in modelling the faulty material disturbance.

- *Supplier providing incorrect material:*

This disturbance assumes that the supplier provides material that is not the same as that ordered. For the system, it would be reflected as an inventory disturbance, and can be

modelled as in modelling the faulty material disturbance. However, the magnitude in this case would be large in comparison to the faulty material disturbance.

The creation of the relevant routines for the modelling will be addressed in section 3.3. The brief description on development of the simulation model, and the model verification and validation conducted will be given in sections 3.4 and 3.5, respectively. In section 4 the contextual model is utilised for several tests of “what-if” scenarios in the presence of disturbances. The purpose is to investigate how the various disturbances affect the behaviour of the supply chain system controlled by the inventory policies, and to give a qualitative characterisation of their performances.

3.3 Modelling disturbance routines

Some DES languages such as SIMAN, ARENA, and SIMSCRIPT have both process-oriented and event scheduling schemes capabilities, see (Cassandra & Lafortune, 1999). Notably, the event scheduling scheme capability would allow the programmer to control the logic flow (including the occurrences of events) in the simulation model. If the programmer has the flexibility to control the logic and events flow, then the implementation of disturbances could be realised by creating the appropriate routines. The approach to be described here is devised to create the DES routines for the modeling of the disturbances.

In order to implement the disturbances as specified in Table 4, the following steps have been taken.

- a. Define a set of events at each particular resource. The resources refer to the inventories and production machines of interest.
- b. Define a set of states for each resource.
- c. Draw a DES sample path (a timing diagram with arrows with events denoted by arrows at the times they occur). A sample path can only jump from one state to another whenever an event occurs.
- d. Indicate on the DES sample path the state at which the system would be, upon the occurrences of a particular disturbance. By using DES sample path to capture the characteristics of the resource, the desired behaviour of the resource when an unexpected disturbance occurs could be observed and understood.
- e. Give a written implementation on DES, of modeling the particular disturbance.
- f. Utilise ARENA modeling tools (modules) to implement the routines.

The DES sample paths developed in the modeling of the disturbances as listed in column 2 of Table 4 are as follows:

- Varying retailer’s ordering patterns:

Define the set of events for the ordering as $E_{R\text{ order}} = \{ \text{Issue order equals } Q_{\text{nom}}, \text{ Issue order above } Q_{\text{nom}}, \text{ Issue order below } Q_{\text{nom}} \}$

where,

Issue order equals Q_{nom} denotes the ordering of Q_{nom} , [e_1 in Figure 3]

Issue order above Q_{nom} denotes the ordering of above Q_{nom} , [e_2 in Figure 3]

Issue order below Q_{nom} denotes the ordering of below Q_{nom} , [e_3 in Figure 3].

Define the set of states for the retailer’s as $X_{R\text{ order}} = \{ Q_{\text{nom}}, \text{ Above } Q_{\text{nom}}, \text{ Below } Q_{\text{nom}} \}$

where,

Q_{nom} denotes the nominal quantity being ordered by the retailer, [x_1 in Figure 3]

Above Q_{nom} denotes the quantity being ordered by the retailer is above nominal, [x_2 in Figure 3]

Below Q_{nom} denotes the quantity being ordered by the retailer is below nominal, [x_3 in Figure 3].

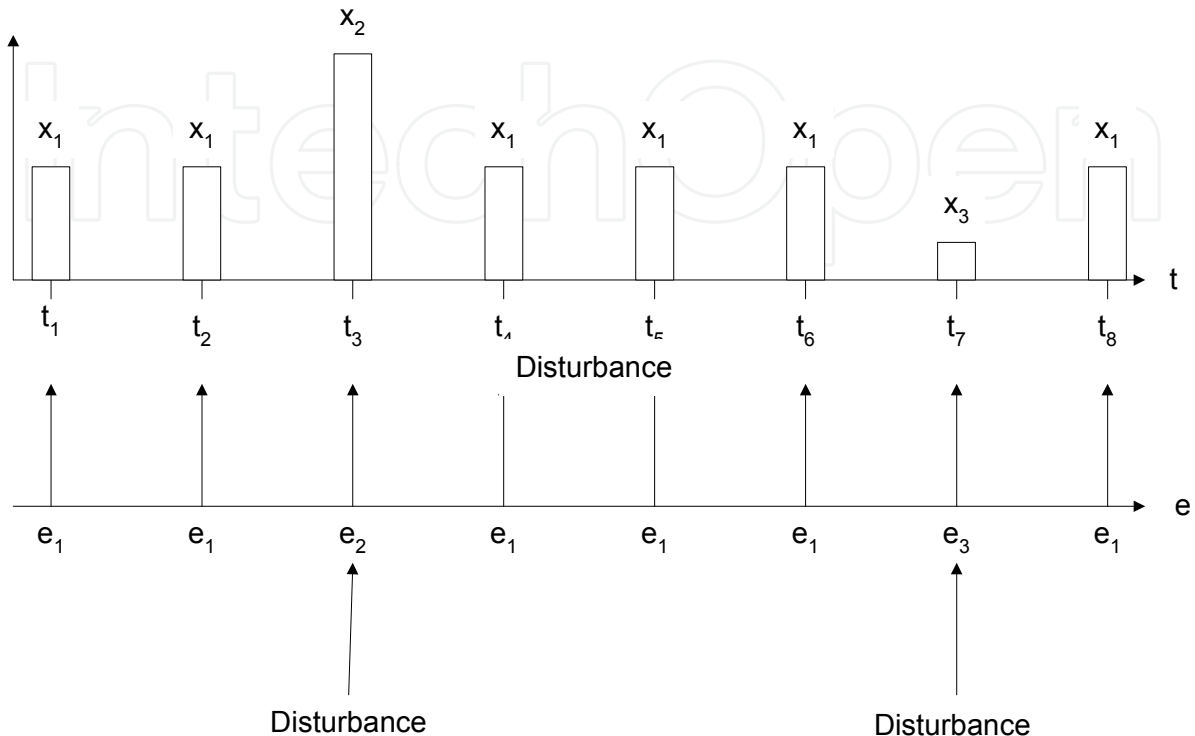


Figure 3. Sample paths for retailer's ordering pattern

The retailer's ordering pattern would be modeled to behave as follows: Whenever e_1 occurs, the state of the order would be x_1 . This can be thought of as the system being in its steady state. For the case of disturbances, the state would be x_2 when e_2 is triggered, and if e_3 is triggered the state would be x_3 . The triggering of event e_2 or e_3 would cause the ordering pattern to deviate away from the nominal values.

The routine for creating the retailer's ordering pattern would be as follows:

During no-disturbance, e_1 , the state $x_1 = k * x_1$, where $k=1$

Upon the occurrence of a disturbance, e_2 , the state $x_2 = k * x_1$, where $k > 1$

Upon the occurrence of a disturbance, e_3 , the state $x_3 = k * x_1$, where $k < 1$

Example: The nominal order quantity is 100 units, hence for $k=1$ (during no-disturbance), the order is 100 units. To create a Type I disturbance (changing operating points) the value k is adjusted, say $k=1.3$, the order is 130 units, and if say $k=0.8$, the order is 80 units.

- Modeling machine breakdown

Define the event set for the machine as

$$E_{\text{machine}} = \{ \text{arr}_{\text{mach}}, \text{dep}_{\text{mach}} \}$$

where

arr_{mach} denotes an arrival of materials for production, [e_1 in Figure 4]

dep_{mach} denotes a departure of goods from machine, [e_2 in Figure 4].

Define the state for the machine as

$$X_{\text{machine}} = \{ B, I, D \}$$

where

B denotes that the machine is in the busy state, [x₁ in Figure 4]

I denotes that the machine is in the idle state, [x₂ in Figure 4]

D denotes that the machine is in the down (failure) state, [x₃ in Figure 4].

A DES sample path for this system is as shown in Figure 4.

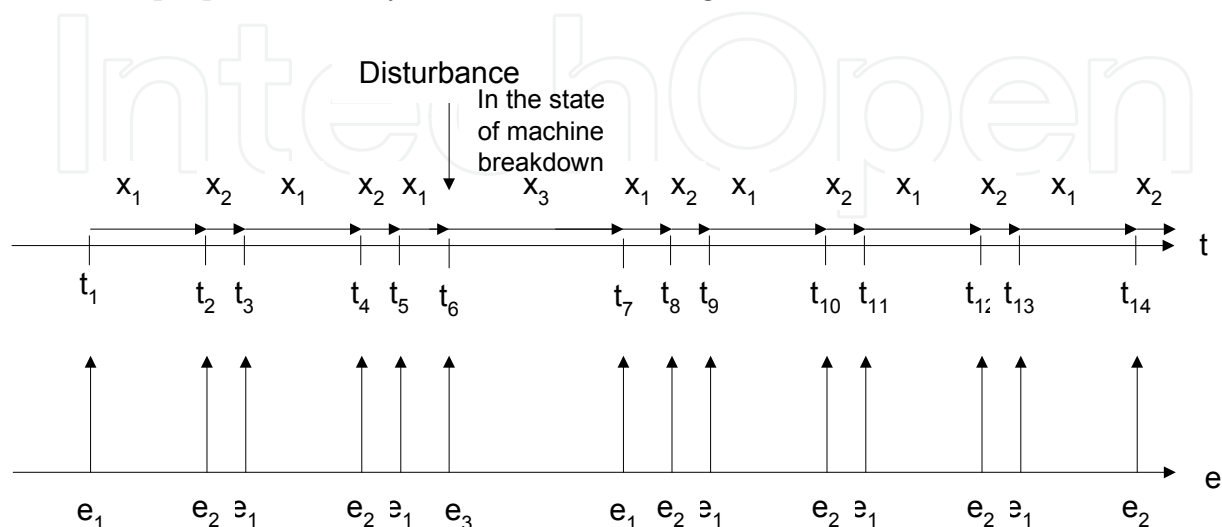


Figure 4. Sample paths for machine breakdown

The behaviour of the system would be as follows: Whenever e₁ occurs, the state of the resource would be x₁ (between t₁ and t₂ time interval). The state of the resource would be x₂ (between t₂ and t₃ time interval) when e₂ is triggered. Modeling this disturbance will amount to initiating event e₃ followed by the event e₁ after the time duration of machine breakdown. Upon the occurrences of a disturbance (the point of time when e₃ is triggered), as shown to be at t₆, the state of the packer/filler machine would then be x₃ (between t₆ and t₇ time interval).

Example: The modeler/programmer has the flexibility to create the occurrences of e₃. Say, e₃ occurs a day after a weekly order is issued, and the duration of the breakdown (the duration of time between t₆ and t₇) can be assigned as 3 days or 72 hours.

- Modeling faulty material

Define the event set for the printer production as

$$E_{\text{Printer production}} = \{ \text{No faulty}, \text{With faulty} \}$$

where

No faulty denotes the production batch is 100% acceptable, [e₁ in Figure 5]

With faulty denotes the production batch is with faulty, [e₂ in Figure 5].

The state of the printer production can be written as

$$X_P = \{ q, q \text{ less faulty} \}$$

where

q denotes the production batch of printed labels (from printer company), [x₁ in Figure 5]

q less faulty denotes the production batch with faulty labels, [x₂ in Figure 5].

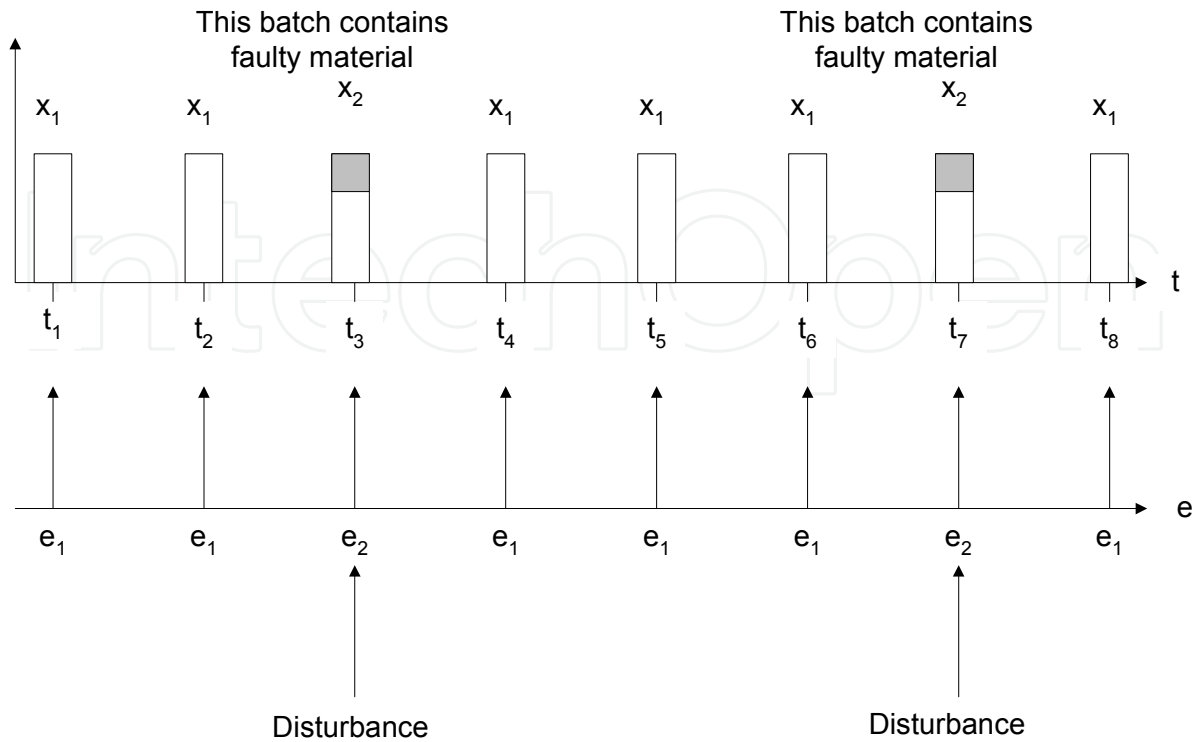


Figure 5. Sample paths for packer/filler printed labels stock

The sample path is as shown in Figure 5. The behaviour of the system should be as follows: Whenever e_1 occurs, the state of the resource (printer production) would be x_1 . For the case when e_2 is triggered, the state would be x_2 where the shaded region indicates the portion of the production is faulty.

The routine for creating this disturbance would be as follows:

Upon the occurrence of a disturbance, the production at printer will be q units, but due to faulty material, the quantity delivered to packer/filler will be q units less the faulty.

Example: The modeler/programmer has the flexibility to create the occurrences of event e_2 . For example, e_2 occurs and the batch being produced is assumed to have faulty material (assigned with a % faulty, say α). Upon completion, a portion that is assigned as faulty is disposed, and the other portion $(1 - \alpha) * q$ is delivered to the next facility (company).

- Modeling late delivery

Define the event sets for delivery of goods as

$$E_{\text{delivery}} = \{\text{Start deliver goods, Deliver goods within normal time, Deliver goods longer than normal time}\}$$

where,

Send goods denotes the sending of the completed goods, [e_1 in Figure 6]

Deliver goods within normal time denotes the completed goods is delivered within time, [e_2 in Figure 6]

Deliver goods longer than normal time denotes the completed goods is delivered late, [e_3 in Figure 6].

Any goods delivered in less time will be considered as within normal time, since the range of time is still within the specified 3 days period and could not adversely affect the parameters being measured.

The states of the receiver (inventory) can be written as follows:

$$X_{\text{receiver}} \{ \text{Receive goods on time, Receive goods late} \}$$

where,

Receive goods on time denotes the completed goods arrives within normal time, [x_1 in Figure 6]

Receive goods late denotes the completed goods arrives late, [x_2 in Figure 6].

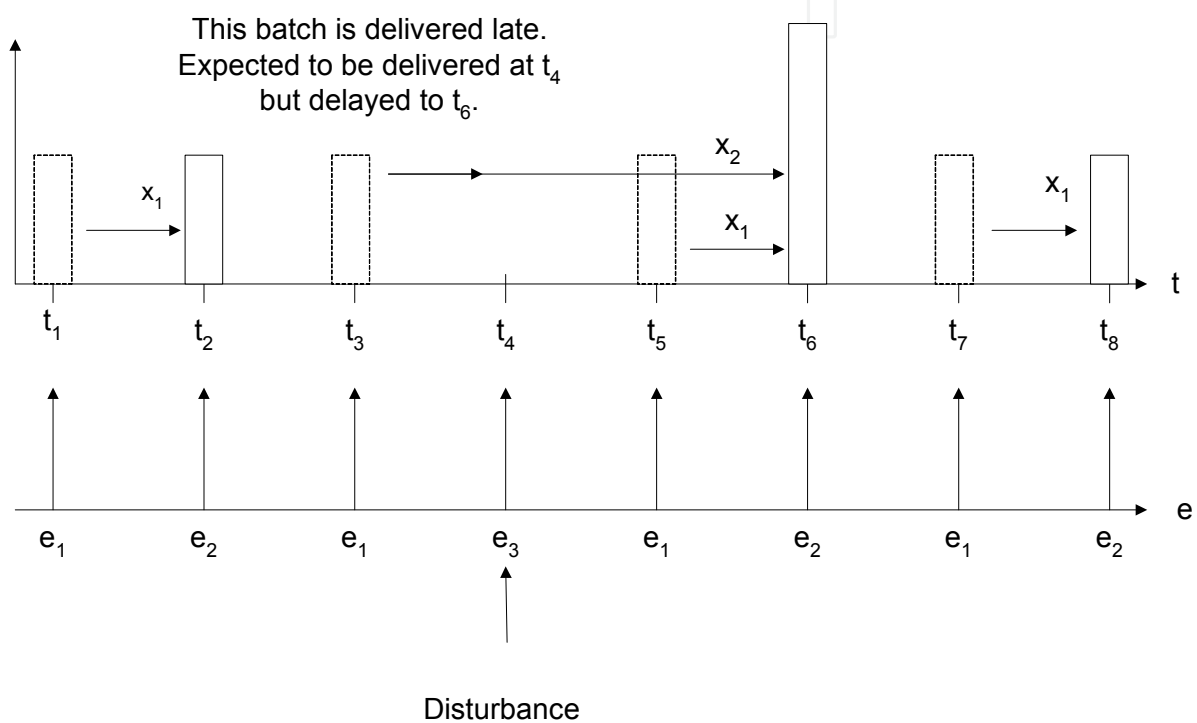


Figure 6. Sample paths for late delivery

The sample path is as shown in Figure 6. As an illustration, the behaviour of the system should be as follows: When e_1 occurs, the printer production will send the completed batch of goods to packer/filler. For normal delivery (event e_2), the goods will be received at the indicated time. For late delivery (event e_3), the goods will be subjected to additional delay time, t_{delay} . For normal delivery $t_{\text{delay}} = 0$ hours. For late delivery $t_{\text{delay}} = \{24$ (for 1 day delay), 48 (2 days delay), 72 (for 3 days delay), etc. $\}$.

The routine for creating this disturbance would be to use a delay block between printer production and packer/filler inventory, where during normal delivery this delay would be zero (no delay), and positive non-zero otherwise (with delay).

3.4 Development of the simulation model

The design of the simulation model of the supply chain system is formulated as follows. The first step is to identify, express and modify the supply chain system directly in terms of its behaviour. The next step is to design the model according to the requirement that it will be

utilised as an experimental tool to allow the study of some inventory and production control methods on the whole supply chain system. The following features have to be provided:

- Reading from an input file (for example, a text file) that will represent the order arrivals from the end customer.
- Writing output data to an output file (for example, Excel) for numerical and graphical representations of the variables of interest. These observations could then be analysed, and consequently the true system performance measures can be estimated.

The next following step is to define the mechanism to facilitate the coordination of the flow of products (materials) in an efficient manner with the use of messages. For instance, the controlling of the flow of system entities (products) could be addressed by manipulating the available order information (eg., the quantity to order) together with the information from each facility (eg., the inventory level) upon the occurrence of a certain event at a particular point in time. Finally, the next step is to adopt the concept of 'modularity', which is important for reducing the amount of time to build the implementation model.

A general coverage on how to carry out effective simulation modelling, analysis, and projects in ARENA environment can be found in Kelton *et. al.* (1998). The model is represented by a number of unique sub-models. These sub-models represent a central clock, an inventory facility, a production facility, the 'managerial unit' (logic decisions), an arrival of orders for materials, and a writing routine, as required in the complete model. The basic building blocks for each sub-model is developed using the modules templates in ARENA, for examples, the resources, systems entities, and delays. One of the main characteristics of ARENA modelling orientation is the use of the concept of entity-based, and process orientation. For this reason, the crucial step in the development of the implementation model is to successfully laying out the sequence of activities required to move the entity through the system, and supplying the data required to support these entity actions. Figure 7 illustrates the process chart representation of the implementation model. Nevertheless, it is not the intention of this paper to discuss in great detail on the building of the simulation model. More detail explanation can be found in Saad (2003).

3.5 Model verification and validation

The process of determining the correctness of model operation typically consists of two separate functions: verification and validation. Verification and validation activities is an on-going process throughout the modelling and simulation phases. A number of researchers including (Caughlin, 2000), suggested that whilst verification seeks to show that the computer program performs as expected and intended, validation, on the other hand, establishes that the model behaviour validly represents that of the real-world system being simulated. Both processes involve system testing that demonstrates different aspects of model accuracy.

One normally used technique is the *parameter variability-sensitivity analysis*. (Sargent, 2000), describes this analysis as follows. It consists of changing the values of the input and internal parameters of a model to determine the effect upon the model's behaviour and its output. The same relationships should occur in the model as in the real system. Those parameters that are sensitive, i.e., cause significant changes in the model's behaviour or output, should be made sufficiently accurate prior to using the model. A similar technique is used in the validation process for this work. Simulations were conducted to observe the effect of

changing the production rate at company C on the inventory levels of company C and company D, respectively.

In each case, the average entities' waiting times at these inventories were recorded. It shows that a reduction in the production rates, increases the average waiting time in the blank labels inventory of company C: implying that if company C were to reduce its production units per day, there would be some significant risks of stock-out in the inventory levels in company D. Simulations were also made to observe the effect of changing the production rate at company C on the percentage of orders filled (which should be maximized). The result suggests that the behaviour of the system does match the expectations of the behaviour of each element in the model. The results of the validation exercise is comparable to the available knowledge about the actual system.

4. Simulation results and analysis

This section will examine and analyse several "what-if" scenarios in the presence of disturbances against different policies. The number of possible scenarios are combinatorial in terms of possible disturbances and hence not all would be tested. Likewise, there are various types of inventory policies that could be tested, see (Silver *et.al.*, 1998). However, the investigation in this work will be focussing on the inventory policies discussed in section 2.

The detailed descriptions of the performance measures to be used for evaluation in this study is presented in Table 3. The performance measures have been defined for measuring the effectiveness and the efficiency of the decision policies. Different ordering policies will be applied at the packer/filler company and their performances will be analysed and compared.

Performance measures	Descriptions
Time to reach steady state	The ideal response of the packer/filler's inventory level to a step change in demand (retailer's orders) is that it should react as quickly as possible in adapting to the post step change level of demand, or to a new level.
Average stocks levels ^a	The inventory level is to be sustained at a low level.
Average variation in order quantity set to printer	The order variations should be kept small, since this can mean that the replenishments are made on a regular basis with small variations in the order sizes.
Number of emergency orders	The number of emergency orders is to be kept low, since this can mean that the extra cost incurred in the replenishments can be minimised.
Risk of stock out	Risk of stock out is to be kept low, since this reflects the ability to offer a reasonable level of service to the customer.

Table 3. Performance Measures, and Descriptions for the Model.

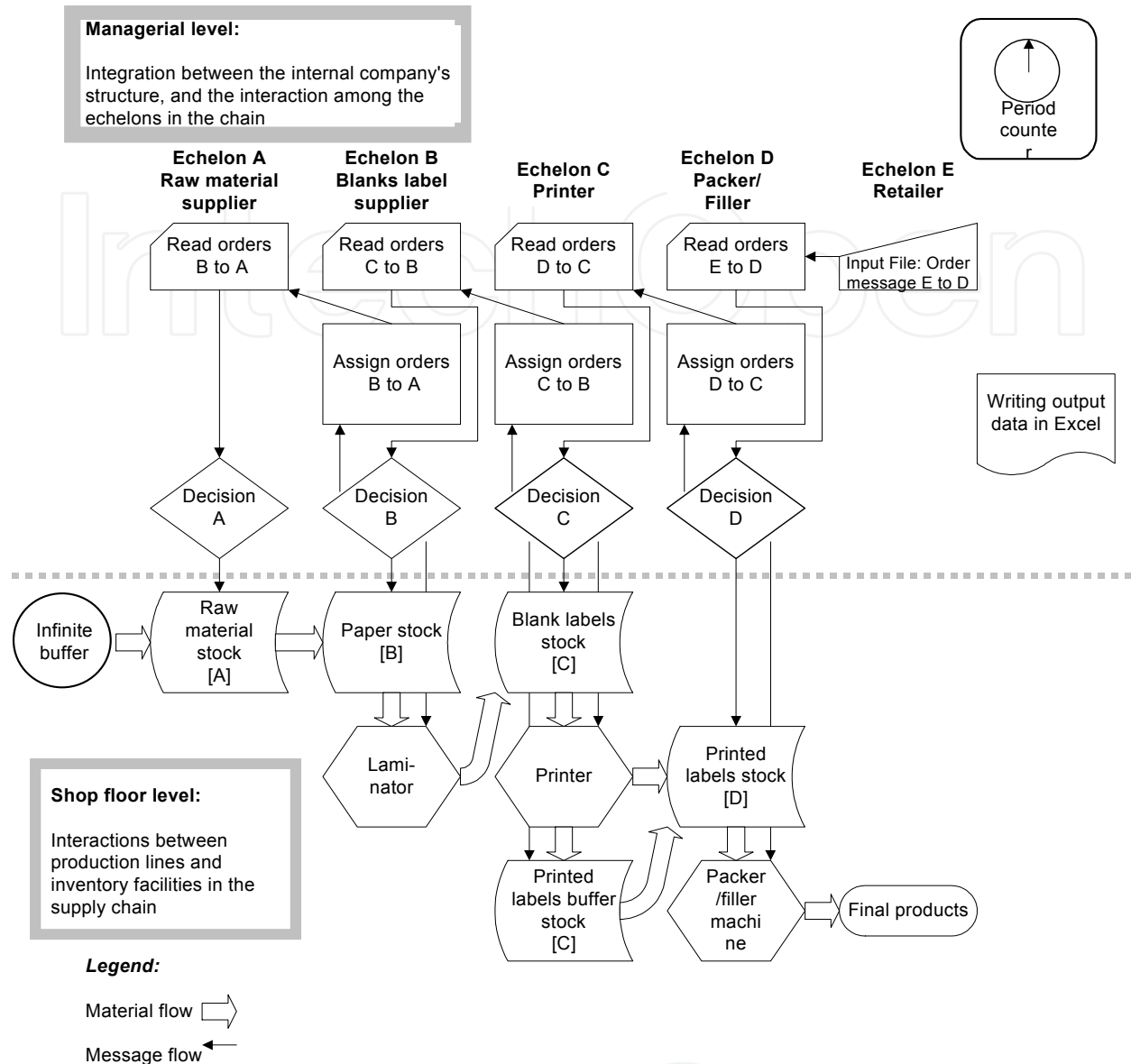


Figure 7. A process chart representation of the implementation model

4.1 Simulation example 1:

Type 1 disturbance - Changes in product demand

The simulation for Type 1 disturbance is to understand the consequences when those parameters that might be open to change in the future, particularly when the input patterns (retailer demand) were varied. The simulation presented here focuses on the pulse type of various magnitudes in the product demand from retailer, with the steps of the pulse being varied to +20%, +40%, +60%, +80%, and +100% of the normal demand (100 units per day). To compare the effectiveness of each policy in the presence of variations in the input pattern, two order policies (i.e. the (s,S) and the Pseudo PID inventory policies) were

considered and the results were tabulated in Table 4. The (s,S) policy (test PD-a) is able to keep the number of risks down to zero, for most cases (pulse size 120 ~ 180). For the pseudo PID policy (test PD-b), the risks start to occur earlier (for pulse size 160 ~ 200). However, the (s,S) policy forces the packer/filler to keep comparatively large stocks: implying that having larger stock reduces the risk of stock-out. The results imply that the (s,S) policy is more robust than the Pseudo PID policy in keeping the risk of stock-out low if disturbances are in the form of larger product demand period. In this context, robustness implies that the policy is yielding performance that is insensitive to external disturbance and parameter variations.

	Order decision at packer/filler, u_D		
Input (Pulse demand pattern)	Output Performance	Test PD-a (s,S)	Test PD-b <i>Pseudo PID</i>
120 units (+20% demand)	Stock levels at packer/filler: l_{Dmax} l_{Dmin} <i>Risk of stock-out</i>	1040 160 0	990 200 0
140 units (+40% demand)	Stock levels at packer/filler: l_{Dmax} l_{Dmin} <i>Risk of stock-out</i>	1120 20 0	1080 100 0
160 units (+60% demand)	Stock levels at packer/filler: l_{Dmax} l_{Dmin} <i>Risk of stock-out</i>	1380 120 0	1170 0 1
180 units (+80% demand)	Stock levels at packer/filler: l_{Dmax} l_{Dmin} <i>Risk of stock-out</i>	1460 60 0	1320 0 1
200 units (+100% demand)	Stock levels at packer/filler: l_{Dmax} l_{Dmin} <i>Risk of stock-out</i>	1600 0 2	1500 0 2

Table 4. Comparison on the effectiveness of the decision (policy) in the presence of variations in the input pattern, based on the performance metrics.

4.2 Simulation example 2:

Type II disturbance - Manufacturing capacity

The work presented here focuses on uncertainties during the occurrences of machine breakdown. Several performance metrics will be considered in making a comparison on the effectiveness of the different order decisions (inventory policies) at the packer/filler.

A decision-maker may want to know how these figures (performance metrics) change if the day of the breakdown is different. Specifically, the simulation will consider two cases: (a) breakdown occurs before the regular order is made (the effect of ignoring the regular order), and (b) breakdown occurs after regular order has been issued (if regular order is processed).

In all tests, the model was subjected to the same test conditions: simulation time of 60 days, machine breakdown period of 4 days (96 hours), and assuming a smooth demand from retailer (100 units per day). Performance results for the first case are displayed in Table 5a, and for the second case in Table 5b.

Performance metrics	Order decision at packer/filler, u_D		
	Test MB-1a <i>Generic</i>	Test MB-1b (s,S)	Test MB-1c <i>Pseudo PID</i>
Time to return to steady state (in days)	14	28	28
Average stock levels at D l_{Dav} , and at C l_{Cav}	395 2928	655 2768	515 2796
Average variation in order quantity set to printer	60	160	94
Number of emergency orders, E at day d	1	1	1
Risk of stock out	2	2	2
Number of order batch undelivered	1	1	1

Table 5a. Comparison on the effectiveness of the decision (policy) in the presence of disturbance (machine breakdown occurs before regular order is made), based on the performance metrics.

Performance metrics	Order decision at packer/filler, u_D		
	Test MB-2a <i>Generic</i>	Test MB-2b (s,S)	Test MB-2c <i>Pseudo PID</i>
Time to return to steady state (in days)	14	28	49
Average stock levels at D l_{Dav} , and at C l_{Cav}	620 2637	655 2632	615 2647
Average variation in order quantity set to printer	0	160	99
Number of emergency orders, E	0	1	1
Risk of stock out	2	2	2
Number of order batch undelivered	1	1	1

Table 5b. Comparison on the effectiveness of the decision (policy) in the presence of disturbance (machine breakdown occur after regular order is made), based on the performance metrics.

One can see that the tests for (s,S) policy (see Test MB-1b and Test MB-2b) show a similar output performance, indicating that even though the system is experiencing two different disturbances of machine breakdown, the effect will be the same throughout. This could suggest that the (s,S) policy provides good regulation in maintaining the stock. Tests for the generic and the pseudo PID show an increase in the average stock level of the packer/filler company, when a machine breakdown occurs after the regular order has been issued. Note that the lead times for all the tests (Test MB-1a ~ Test MB-1c, and Test-MB-2a ~ Test MB-2c) are assumed to be the same.

4.3 Simulation example 3:

Type III disturbance - Inventory disturbances

In modeling this disturbance, the printer will print the amount as ordered, but the fault is modeled to take effect after the printing is completed. The argument is, if the printer production and delivery are kept separate, then this can be modeled more effectively. It is assumed that 20% of the order being delivered to packer/filler from printer to be faulty.

4.3.1 Type III-Faulty material

The tests (Test FM-a ~ Test FM-c) assumed 20 % of material delivered from printer to packer/filler is faulty. The interest is focused on how effective the control schemes (inventory policies) are in regulating the system to the occurrence of the disturbance (faulty materials). The performance results are displayed in Table 6.

Performance metrics	Order decision at packer/filler, u_D		
	Test FM-a <i>Generic</i>	Test FM-b (s,S)	Test FM-c <i>Pseudo PID</i>
Time to return to steady state (in days)	14	14	42
Average stock levels at D l_{Dav} , and at C l_{Cav}	519 2734	557 2737	546 2852
Average variation in order quantity set to printer	86	30	8
Number of emergency orders, E at day d	1	0	0
Risk of stock out	0	0	0

Table 6. Comparison on the effectiveness of the decision (policy) in the presence of disturbance (faulty materials), based on the performance metrics

Pseudo PID (see Test FM-c) is shown to reduce the average variation in order quantity set to printer. Although the time to return to steady state is relatively large (slow response), this may not be a disturbing factor considering that the average stock level at packer/filler is relatively low compared to the case with the (s,S) policy.

4.3.2 Type III-Late delivery

Two tests were performed. First test is a comparison on the effectiveness of each scheme (inventory policies) to the occurrence of late deliveries. The second is an analysis on the effect of the late deliveries that last for a certain duration of days, on the risk of stock-outs and to the number of undelivered items (batch ordered).

The first set of tests:

Table 7 compares the effectiveness of the different control scheme (inventory policies) to late deliveries, lasting 4 days. The summary of the findings is as follows: Tests LD-a, and LD-c indicate that the generic policy is effective in regulating the inventory at the packer/filler. The (s,S) policy (Test LD-b) can keep the average inventory level low, but the order issued to printer company is larger than the other policies. The Pseudo PID is slow to reach steady state, but performs well in other aspects of performance.

Performance metrics	Order decision at packer/filler, u_D		
	Test LD-a <i>Generic</i>	Test LD-b (s,S)	Test LD-c <i>Pseudo PID</i>
Time to return to steady state (in days)	14	28	63
Average stock levels at D l_{Dav} , and at C l_{Cav}	770 2759	655 2632	690 2585
Maximum order quantity to printer, u_{Dmax} .	700	1400	810
Average variation in order quantity set to printer	100	160	147
Number of emergency orders, E at day d	1	0	1
Risk of stock out	2	2	2
Number of order batch undelivered	1	1	1

Table 7. Comparison on the effectiveness of the decision (policy) in the presence of disturbance (late deliveries, duration of 4 days), based on the performance metrics.

The second set of tests:

The analysis is on the effect of the late deliveries lasting a certain duration of days, on the risk of stock-outs and to the number of undelivered items.

Graph a of Figure 8, shows that for (s,S) policy, the risks of stock-out increases almost linearly from one (duration of 3 days of late delivery) to five (duration of 7 days of late delivery), and then settles to five (duration of 8 days onwards of late deliveries). For the pseudo PID policy, at first the risks emerges with just one (from duration of 3 days of late delivery) and then settles to two from duration of 4 days onwards of late deliveries. Graph b indicates that the number of undelivered items (ordered batch) were maintained with one for the pseudo PID policy. For the (s,S) policy the number of undelivered batch increases linearly and then stabilises to four occurrences from duration equals 7. The results indicate that the pseudo PID policies perform well in keeping the number of stock-outs low. On overall, results revealed the robustness of the various decision policies to the different types

of disturbances. In particular, it was seen that pseudo PID, a policy derived from the control system view point, exhibited much more robustness than other policies.

The model developed in this work was limited to the analysis of situations that have been discussed in this chapter. However, the modeling and simulation for other disturbances for example, the decision making at another company, for instance the printer company, would be similar and straightforward to what that has been presented.

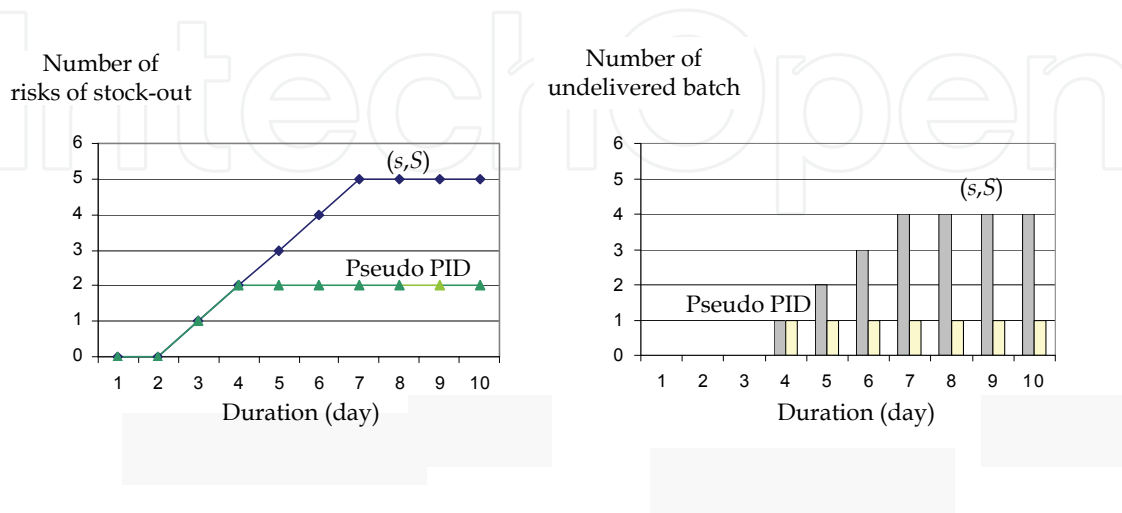


Figure 8. Risk of stock-outs and the number of undelivered batch for a specified duration of late deliveries. Graph a. Risk of stock-outs versus duration of late deliveries. Graph b. Number of undelivered items (batch ordered) versus duration of late deliveries.

5. Conclusion

Simulation using a DES is an effective tool for the dynamically changing supply chain variables, thus allowing the system to be modeled more realistically. The modelling, simulation, and analysis of a supply chain discussed in this chapter are a preliminary attempt to establish a methodology for modelling, simulation and analysis of a supply chain using a DES. There are further problems to be considered both in the development of the model and the experimental design.

The main contributions of this work are:

- As a DSS, the simulation model represents important characteristics of a packaging industry supply chain and incorporate the complex interactions that may exist between the various components in the system. Importantly, the model was designed with easily adaptable structure where rules (inventory policies) and model variables can be modified. By devising appropriate experimental design, several tests can be performed to imitate some realistic situations (the presence of disturbances). The results can then be analysed to provide information to a decision-maker from which solutions can be inferred.
- The detailed comparisons of three inventory policies (the *generic*, the (s,S) , and the *pseudo PID*) for a production-inventory control under dynamic conditions were given. The *pseudo PID* policy, which has not been reported elsewhere, has been shown to have

several advantages as an inventory control policy. Qualitative behaviour of supply chain to different policies were confirmed through detailed quantitative analysis.

The future work should include:

- Development of a decision-support system for supply chain.
- Developing a decision-support system (DSS) software on the basis of the proposed approach with the consideration of more general and easy building blocks, and taking practical situation into account, would be beneficial. The particular emphasis should be given on development for a larger and demanding systems, such as multiple suppliers, and multiple customers (retailers).
- Verification and validation of the modelling approach.
- Applying the modelling approach to a different type of supply chain topology, in order to verify and validate the technique under different classes of systems will demonstrate the generality of the approach. The issue of verification and validation when real data are available has not been done here. If such data were available, integrating the method advocates in this work is with that based on real data would be an interesting paradigm in verification and validation.
- Modelling multiple disturbances.
- Although the *contextual load model* can simulate the complex behaviour of the supply chain from various scenarios, it is still not sufficient for most applications because the outcome of the analysis are based on the assumption that each disturbance occurs independently. The extension on the *contextual load* modelling, to understand how each controller (inventory policy) reacts to a combination of several disturbances (multiple disturbances), would still be required.
- Evaluation of inventory control policies.
- The evaluation of other inventory policies that already exist, and the modelling and evaluation of newly proposed inventory policies, for example new control theory motivated policies such as gain scheduling incorporated into the *pseudo PID* inventory control model, to provide insights and better understanding of each of the inventory control policy, would need to be explored.
- The work presented in this chapter has contributed to an improved understanding of the procedure for modelling, simulation and analysis of a supply chain system with a discrete-event simulation tool. Even though the approach presented here offers some promising tools, much work remains to be done to produce a systematic methodology for building a model of high complexity in nature, like the supply chain.

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Traditionally supply chain management has meant factories, assembly lines, warehouses, transportation vehicles, and time sheets. Modern supply chain management is a highly complex, multidimensional problem set with virtually endless number of variables for optimization. An Internet enabled supply chain may have just-in-time delivery, precise inventory visibility, and up-to-the-minute distribution-tracking capabilities. Technology advances have enabled supply chains to become strategic weapons that can help avoid disasters, lower costs, and make money. From internal enterprise processes to external business transactions with suppliers, transporters, channels and end-users marks the wide range of challenges researchers have to handle. The aim of this book is at revealing and illustrating this diversity in terms of scientific and theoretical fundamentals, prevailing concepts as well as current practical applications.

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