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Modeling the multi-channel section in the supply chain system using the multiserver queue theory

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ABSTRACT

Industry generally consists of a supply chain system. The main constituents of any supply chain system are suppliers, manufacturers, distribution centers and retailers. The system configuration can be straight chain, branched, cyclic, or a combination of all. An analytical model is needed to study system behavior as a result of the dynamics of its constituents. Modeling a multi channel section becomes quite a challenging job in this regard. A method of modeling the multi-channel section will be discussed in this paper by adopting the concept of multi-server queues. As is well known, in a multi-server queue there is a branching point at which the flow of entities begins to spread across a number of parallel servers. In modeling perspective of this paper, the branching point is in the buffer (finished good warehouse in the factory, i.e. the focal echelon). That is the end of the waiting line from which the entity specifically moves to one of the servers, or in this context it is called a channel. In this paper the number of channels can be any, generalizable, can be more than two. Hence, the subsystem studied includes a factory, finished product warehouse and several distribution centers. Factory produces by mechanism of (R, r), where R and r are stopping point and production restarting point, respectively. Production stops when the quantity of finished product in the warehouse reaches R units, and will restart the production when the quantity drops to the same or lower than r units. The model is developed under Markovian assumptions by considering the quantities of production rates, number of distribution centers (channels), travel time from factories to each distribution center, delivery lotsize, and the time between arrival of orders from distribution centers. The system under study is seen as a case of two echelons, namely factories and distribution channels. The numerical model obtained is applied to one case example with certain conditions. Comparisons with discrete simulation results give quite small and acceptable differences. So in the future this model can be applied to complement the overall modeling of the supply chain system which is multi-echelon system with multi-channel distribution.

Keywords: *supply chain, multi channel distribution, production restarting point, production stopping time, markovian model.*

Introduction

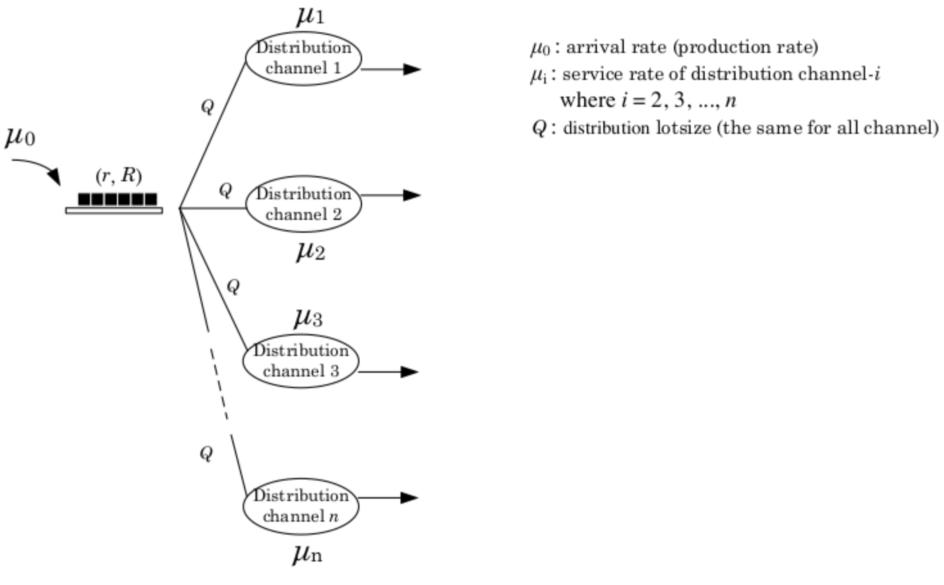
The supply chain system is composed of a series of supplier-factory-distributor-retailer. Each of those subject in the supply chain is generally a company with management that is independent from one another. However, they will collaborate in order to obtain a smooth process for supplying products to end consumers. The number of suppliers on the upstream side of the factory and the number of distribution channels on the downstream side are generally more than one.

Efficiency is one of the determinants of industrial sustainability. Therefore it is necessary to have good cooperation between subjects in the supply chain system. Such cooperation must be based on high integrity, in the spirit that the supply process must create the competitiveness of the products distributed. Various studies have shown that a holistic review of the stock items in the system will minimize the total cost of inventory rather than a partial review of the respective subjects. This shows the importance of supply chain management and its intended integrity.

Various models of supply chain have been described in literature, either in the form of optimization models or performance models (Altiok [1]). Optimization models are more often expressed in the form of integer linear programming, while performance models are in the form of simulation models or queuing network models. The performance model for the supply chain system is quite similar to the performance model for the production line system. A comprehensive review of the performance model of the production line system can also be seen in Dallery and Gershwin [6]. There are two types of production line systems, namely flow lines and transfer lines (Buzacott and Shanthikumar [4]). A flow line model that will be very useful is the model described by Dallery and Frein [5]. In this model, processing at each work station is assumed to be exponentially distributed. The model was built using decomposition techniques. The whole system is aggregated into a two-stage system so that several alternative aggregate systems are formed which are composed of two stages of the process where each stage is an aggregate stage, each representing the upstream and downstream sides. Overall this aggregation gives the form as if the original system was decomposed into several two-stage subsystems.

Like flowlines, supply chain systems can also be viewed as queuing network systems. The only difference is the distance between the stages. In a production line system, the distance between stages (i.e. work stations) from one to the next is very close. Whereas in the supply chain system, the distance between the stages (namely echelons) is very far (up to tens to hundreds of km). The supply chain system is a series of sequential echelons that work together to provide the fulfillment of a product to the end consumer. The supply chain system can be identified as a flow line system if the echelons are seen as work stations. This is seen in Altiok [1], Karaman and Altiok [9], Saetta et al [14], and Murdapa et al [11].

By assuming that the supply chain system is a flow line system, Murdapa et al [11] developed the concept of the flow line model in Dallery and Frein [5] into a supply chain system model where there is inventory control at each stage as in Karaman and Altiok. [9]. This gives different subsystem structures when the decomposition analysis technique is applied. Meanwhile, Murdapa et al [10] proposed an analogy concept between a two-channel distribution with a queue of two servers. Products to be distributed are taken directly from the finished product warehouse at the factory. The factory itself monitors the availability of its product stock using the (r, R) mechanism. The lotsizes of the distribution on each channel are assumed to be the same as each other which is denoted as Q (Figure 1). Hence, the proposed preliminary model in Murdapa et al [11] was limited to two channels and has not been validated with simulation results. In this paper, the model is generalized to many channels, and will be validated with simulation results.



μ_0 : arrival rate (production rate)
μ_i : service rate of distribution channel-i
where $i = 2, 3, \ldots, n$
Q : distribution lotsize (the same for all channel)

Figure 1. A single-stage queuing system that is used as a model for a multi-channel distribution system (An extension of Murdapa et al [10])

In a real industry, the supply chain system will always have multiple distribution channels. A model for rapid analysis is needed to facilitate broader discussion of the performance of a more general supply chain system. However, mostly, models were formulated in the form of linear programing that ignore the dynamics of the states of the system. These states in the system will greatly affect system performance. A performance model (Altiok, [1]), which is based on how the system behaves by accommodating the dynamics of the existing states in the system, will be able to help simulate decision scenarios related to the system to be closer to the real system conditions. For this reason, it is important to be able to construct a model that focuses on the multi-channel section of the supply chain system in the type of performance model. In the future, the model will complement with other sections models, forming a complete overall model as the main objective.

This paper generalizes the two-channel case of Murdapa et al. [10] to accomodate any number of channels. Products that are stored in FG Stock will be sent to more than two distribution channels. The duration of the existing processes is assumed to be exponentially distributed, the same as in Murdapa et al [10]. The multi-channel distribution model will be very useful as a basis that will complement the supply chain system modeling, on the problem of several distribution channels. Using decomposition techniques (see Dallery and Gershwin, [6], Gershwin [7], Dallery and Frein [5], Altiok [1], Karaman and Altiok [9], Murdapa et al [11] and Murdapa et al [10]), a more complex supply chain can be analyzed. There, the models in this paper can be very useful.

Research method

This paper is outlined as follows. First, an overview of the hypothetical system under study is presented. The behavior and assumptions regarding the system will be described. Second, the quantities that are known and the quantities to be calculated are notated. Third, system modeling is carried out under the assumption that the system is already in steady state. The conceptualization of state dynamics is expressed in the form of a state transitions diagram, where the system states are defined first. Then, the state transitions are formulated in equations. Next, a numerical calculation algorithm is compiled and written into a computer programming so that experimentation can be carried out quickly. Finally, an evaluation and discussion is conducted regarding the numerical model and its calculation results.

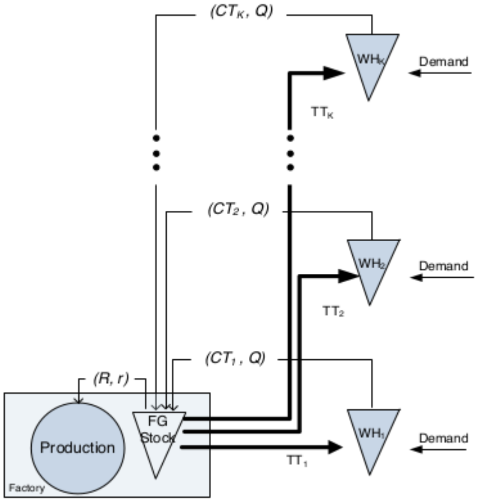


Figure 2. The system studied consists of the following echelons: factory (r, R) and multi distribution channel

Description of the scope of the system under study

The system discussed in this paper is a part of the supply chain consisting of two echelons, namely the factory and distribution channel as shown in Figure 2. The factory is assumed to produce according to the mechanism (r, R), that is, production activities will restart periodically when the inventory level in the finished product warehouse, FG Stock, is less or equal to r. And, the activity stops when the level has reached R. And so on, the mechanism will repeat. Products are sent in Q units to each distribution channel according to their needs. Table 1 shows several symbols of the known quantities (input quantities) related to the system under study.

Table 1. Symbol of known system quantities

r	:	Reproduction point
R	:	Production stopping point
Q	:	*Distribution lotsize* (the same for all warehouses)
μ_0	:	Average production rate
μ_i		Delivery rate to warehouse-i or channel-i
TT_1	:	The average transportation leadtime to the warehouse-1
$\vdots$		
TT_i	:	The average transportation leadtime to the warehouse-n
WS_1	:	Average inventory cycle time in warehouse-1
$\vdots$		
WS_i	:	Average inventory cycle time in warehouse-i
K	:	Number of channels (or number of warehouses)
m	:	Positive integer constant to define nonproduction pathways
k	:	Positive round constant to define negative inventory depth

Modeling

The warehouse in the channel-i in Figure 2 is represented as WH_i. There will be K channels. Shipments from factory to channel-i will take an average of TT_i unit time. Channel-i will place orders to the factory on average every WS_i unit of time. Shipment to the channel-i will occur every $TT_i + WS_i$ so that the shipment rate on the distribution channel-i, μ_i, can be expressed as:

$$\mu_i = \frac{Q}{TT_i + WS_i} \tag{1}$$

In Figure 2, the echelons representing the distribution channel are not yet represented. To accommodate the existence of distribution echelons, Figure 2 can be expressed in the form of a conceptual diagram in Figure 3, where all distribution channel echelons have been clearly added (DCs). The rate of shipment to the distribution channel echelon-i is the inverse of the time between shipments on that channel. This paper focuses on the multi-channel distribution section, shown by the box bounded by the dashed-line. It is assumed for simply that the shipment lot size to each distribution channel is the same, that is Q. The system is a single queue system with several parallel servers.

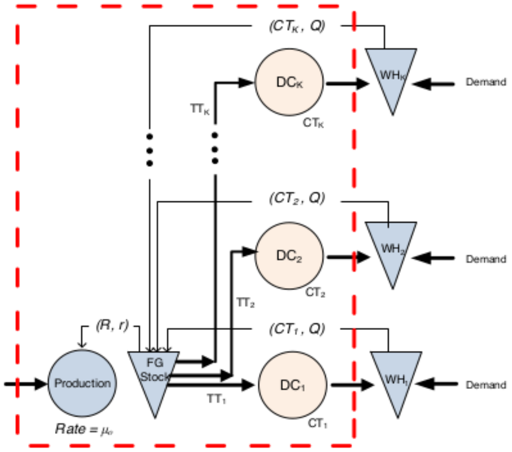


Figure 3. Conceptual diagram of the system under study (in a box with dashed-lines)

The system condistion is described by the level of finished product inventory in FG Stock. State-i where $i = 0$ to ∞ (infinite) means that the level of finished product inventory in FG Stock equal to i units. With this definition, there will be many possible states. The maximum level in FG Stock is R. Backordering is assumed. Then the system condition can be negative, namely when the inventory level is below zero, which means that the factory has a backlog that must be met at a later date. If the probability that the system is in state-i is P_i, then a state transition diagram can be drawn up (Figure 4). Because the theoretical condition of the system can be in the state $i = -\infty$ then it is necessary to truncate the transition diagram only not less than $i = R - kQ$ where k is a large enough positive integer. In this case, the value of k is determined at the beginning of the calculation. Ideally k should be large enough, but not necessarily too large. Assigning k that is too large will cause the computation time to be too long even though it does not affect the final value. An analytical solution would be too difficult to obtain. A numerical solution was used instead.

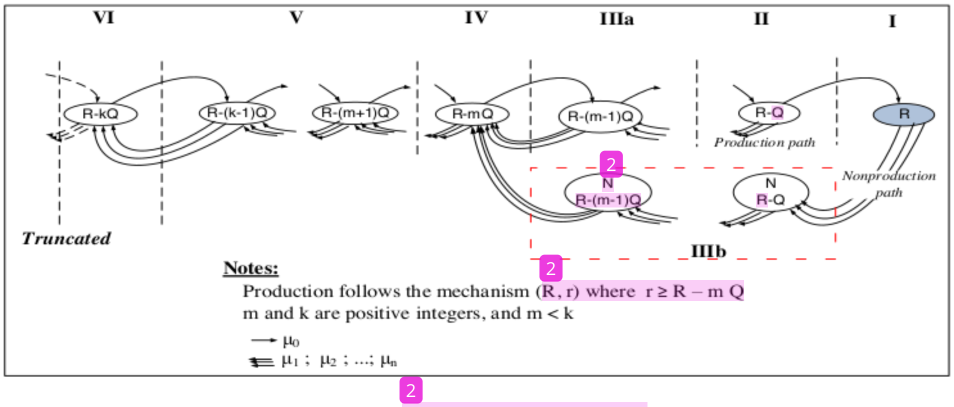


Figure 4. State transition diagram

In the transition diagram, there are two transition paths, namely the production path and the non-production path. On the production path there will be a reduction in stock levels and also production activities. The non-production path occurs when the state is at R. Once R is reached, production activity will stop, then the decrease in the level of inventory (state transitioning to the left) will follow the non-production path. The states that are in the non-production path are indicated by the addition of the notation N. For example, state $(N, R - Q)$ indicates a condition where there is a $R - Q$ unit of product in FG Stock and at that time there is no production activity. The state transition goes out of the nonproduction path when $R - mQ \leq r$ where m is a positive integer constant. Murdapa et al [11] proposed an approach to this case by assuming the actual production lot that occurs one unit at a time according to the mechanism (r, R), being equated with the unit stock level reduction that occurs in Q units.

Under these assumptions, if the input quantities, r, R and Q are given, then:

$$r \geq R - mQ \text{ where } m \text{ is a positive integer} \tag{2}$$

or the value of m must be:

$$m = \left\lceil \frac{R - r}{Q} \right\rceil = \text{smallest integer that is greater than } \left(\frac{R - r}{Q} \right) \tag{3}$$

A suitable transition diagram is shown in Figure 4, which is in principle the same as that depicted in Murdapa et al [10]. The difference is only in the number of channels represented by the left downward curved arrows, which in this study are more numerous. Based on the transition pattern, the state is divided into seven zones, namely zones I, II, IIIa, IIIb, IV, V, and VI. The zones represent the sectors on the state transition diagram which are distinguished from one another by the transition pattern in them. These zones are used to facilitate the generalization of the model. Equations (4) to equation (10) reflect the system transitions that occur. In these equations, the number of distribution channels has been generalized to K.

Zone I: State $i = R$:

$$P_{R-Q} = \frac{[\mu_1 + \mu_2 + \cdots + \mu_K]P_R}{\mu_0} \tag{4}$$

Zone II: State $i = (R - Q)$:

$$P_i = \frac{\mu_0 \, P_{i-Q}}{[\mu_0 + \mu_1 + \mu_2 + \cdots + \mu_K]} \tag{5}$$

Zone IIIa: From state $i = (R - 2Q)$ up to $(R - (m - 1)Q)$: (6)

$$P_i = \frac{\mu_0 P_{i-Q} + [\mu_1 + \mu_2 + \cdots + \mu_K]P_{i+Q}}{[\mu_0 + \mu_1 + \mu_2 + \cdots + \mu_K]}$$

Zone IIIb: From state $i = (N, R - Q)$ up to $(N, R - (m - 1)Q)$: (7)

$$P_i = P_R$$

Zone IV: State $i = R - mQ$:

$$P_i = \frac{\mu_0 P_{i-Q} + [\mu_1 + \mu_2 + \cdots + \mu_K]\left[P_{i+Q} + P_{N,i+Q}\right]}{[\mu_0 + \mu_1 + \mu_2 + \cdots + \mu_K)]} \tag{8}$$

Zone V: From state $i = (R - (m + 1)Q)$ up to $(R - (k - 1)Q)$:

$$P_i = \frac{\mu_0 P_{i-Q} + [\mu_1 + \mu_2 + \cdots + \mu_K]P_{i+Q}}{[\mu_0 + \mu_1 + \mu_2 + \cdots + \mu_K)]} \tag{9}$$

Zone VI: State $i = (R - kQ)$:

$$P_i = \frac{[\mu_1 + \mu_2 + \cdots + \mu_K]P_{i+Q}}{\mu_0} \tag{10}$$

What must be calculated is the probability value of the system being in state n, namely P_n. The system of transition equations (4) to (10) can be solved numerically. In brief, the algorithm for this case is as follows.

STAGE-0: Initialization

a. For a given number of channels K and the stock target value R and the delivery lot size Q:
   1) Choose a value for m, for example $m = 3$
   2) Choose a number k (large enough, but not necessarily too large), for example $k = 50$

b. Set a deviation tolerance value for each iteration cycle, for example $tol = 0.00001$.

c. Assign an initial value for P_i for all i, for example $P_i = 1$ (where P_i is the probability of system being in state i).

d. Save all P_i values to $P_{i,\mathrm{init}}$

STAGE -1: Iteration

Use $P_R = 1$ before normalization as the anchor of the calculation (it never changes the value). Then, using the most recent probability values as input, compute all $P_{i \neq R}$ as follows:

a. Update the value of P_i for the state in zone I using equation (4).
b. Update the value of P_i for the state in zone IIIa using equation (6).
c. Update the value of P_i for the state in zone IIIb using equation (7).
d. Update the value of P_i for the state in zone IV using equation (8).
e. Update the value of P_i for the state in zone V using equation (9).
f. Update the value of P_i for the state in zone VI using equation (10).
g. Normalize P_i so that $\sum P_i = 1$

h. Save the values of P_i as $P_{i,new}$

STAGE -2: Check wether the convergence of the calculations has been obtained

a. Calculate the calculation deviation, $dev = |P_{i,new} - P_{i,init}|$
b. Compare whether the calculation deviation from the most recent iteration with the previous iteration, dev, is already less than the tol. If YES, then go to STAGE-3, the iteration is complete. But if NO, then set $P_{i,new} = P_{i,init}$ and repeat the iteration by returning to STAGE-1

STAGE -3: End

The transition equation in zone II, namely equation (5), is not used because P_R has been selected as an anchor, that is, the value that is set freely before normalization according to stage 0(c) is kept at that value, never updated. Then, the value of $P_{\mathrm{R-Q}}$ is calculated by equation (4). Based on this algorithm, the response variable can be calculated. In this case the response variable is *average finished good stock* (*avgFG*).

Results and Discussion

The system studied consists of factories producing at a certain rate and several distribution channels (more than two). The factory follows the mechanism of (r, R) and submits its production to the warehouse of finished good (FG Stock). It is assumed that this storage process occurs on a unit by unit basis. The maximum amount of stock in FG Stock is R units. Normally, the minimum stock is r units, but it can be less. In fact, the process of delivery products from the factory to each warehouse will occur in batches, that is, a number of Q units (in the case example discussed: 25 units). Delivery occurs periodically following the inventory cycle time in each warehouse. The cycle time depends on the amount of demand from consumers. Shipment of Q units is carried out by certain fleets, for example trucks. Delivery time depends on the distance from the warehouse location to the factory. In this case, the distance can be expressed in units of time.

The approximate analytical model discussed in this paper is more desirable to obtain than the simulation model because of its ability to provide direct calculation results. The value of the response variables can be obtained directly without the need for statistical analysis as in the simulation model. However, an analytical model obtained needs to be checked for suitability by, for example, comparing the results from it with the simulation results.

For example, there are three distribution channels where it is supposed that the delivery time to a warehouse is the same as the inventory cycle time in that warehouse. For warehouse-1: 50 time units to deliver and 50 time units inventory cycle, warehouse-2: 30 units and 30 units, and warehouse-3: 15 units and 15 units of time. Then, the system is analogous to a single stage - multi server queuing system (Murdapa et al [10]). In a manufacturing context, it is a split system where the split process occurs in the "buffer", not on the "machine" (see Helber, [8], for comparison).

Numerical Example

Modeling with a simulation method (discrete) will be much better, in terms of the depth and breadth of the entity types discussed, than mathematical or numerical modeling. For example, Salsabila et al [12] were able to uncover a continuous process problem quite well using discrete simulation modeling, although in this case, experiments with multiple replications were required to obtain good inference. Mathematical / numerical performance modeling, on the other hand, will emphasize more on a holistic depiction of the case being studied where the results of the analysis can be obtained in a more straight-forward manner. By this reason, the approximate analytical model discussed in this paper is more desirable to obtain. The value of the response variable can be obtained directly without the need for statistical analysis as in the simulation model. However, an analytical model obtained needs to be checked for suitability by, for example, comparing its calculation performance to a simulation.

Suppose a factory produces with $r = 15$ and $R = 75$. The rate of production is $\mu_0 = 2.5$ units / time unit. There are three delivery destinations at different locations, namely Warehouse-1, Warehouse-2, and Warehouse-3. Each shipment is transported by truck with a load of 25 units. The distances for each warehouse from the factory are 50, 30, and 15 respectively (which are expressed in units of time). The average inventory cycle times in each warehouse are 50, 30, and 15 respectively (expressed in units of time). The calculation results show that: the average amount of inventory in the finished product warehouse is 36.36 units. An equivalent simulation model is compiled in the ARENA simulation software by referring to Altiok and Melamed [2]. Table 2 summarizes the comparison of the output of the numerical model and the simulation model.

Table 2. Comparison of the average value of Finished Good Stock obtained from two models (Numerical vs Simulation)

												average
Average Finished Good Stock (avgFG)	Numerical	36.36										36.36
	Simulation	47.79	39.84	35.56	36.95	41.23	34.63	41.66	38.99	31.63	36.83	38.51

To see whether the difference is significant, a t-test is carried out using the following steps (Bluman,[3]):

Step-1: Hypothesis statement:
H_o: Numerical result $=$ simulation result (as claim)
H_1: Numerical results $\neq$ simulation results

Step-2: At $\alpha = 0.05$ with $d.f. = 9$, the critical values are: ± 2.262

Step-3: The t-test value:

$$t = \frac{\bar{X} - 36.36}{s/\sqrt{n}} = \frac{28.51 - 36.36}{4.49/\sqrt{10}} = 1.514$$

Step-4: Because the t-value is between critical values: $-2.262 < 1.514 < 2.26$
then the null hypothesis is accepted.

Step-5: In this case, there is sufficient evidence to support the claim that the numerical model and the simulation model provide the same calculation results for the *average FG Stock*.

In the numerical model, the delivery process that occurs in batches has actually been "forced" to occur in units per unit by flattening it in the form of equation (1). However, because the developed transition diagram has accommodated this batch process, the result looks quite satisfactory. Then, the delivery lot size in this discussion must be the same for all channels, i.e. Q units. In real case, the delivery lot size may differ from one channel to another, so in general the model cannot be used. However, this model can still be used with the equivalent method. This should be the next research topic. The multi-channel situation in the supply chain system is common. Hence, this model will be very useful for completing the problem of modeling complex supply chain systems with multi-channel distribution.

Conclusion

A two-echelon supply chain system, namely factories and distributions with multiple channels, can be viewed as a single stage multi-server queuing system. The branching points to several distribution channels are located in the finished product warehouse. In this case the factory is assumed to produce by the mechanism (r, R). Shipment lot size to each channel is the same, which is Q units. The warehouse distance in each channel can differ from one another, where the distance is expressed in units of time. Inventory cycle time in each warehouse may also vary between warehouses. This inventory cycle time will accommodate the arrival rate of customer demand which is not involved in this study.

With markovian analysis, the state transition diagram in the system provides seven zones. The compiled system of equations is solved numerically by setting one of the states (namely state R) as the anchor of the calculation. For a given case example where the plant is producing at a rate of 2.5 units per unit time under the mechanism $(r, R) = (15.75)$ and delivery with an amount $Q = 25$ units to three target locations with different distances (and product consumption rates which is also different as reflected by the different inventory cycle times), it is found that the model which is arranged based on the single stage queuing model is quite satisfactory when compared with the calculation results using the simulation model.

The model obtained can be used to complement the multi-echelon supply chain system modeling with multi-channel distribution. However, one assumption of the same lot size for all channels can be relaxed in subsequent studies in order to be closer to the real system conditions.

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