System Dynamics Modeling of Multi-Channel Supply Chain System: A Hypothetical LPG Distribution with Disloyal Household Customers

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Submitted: 20 June 2022, revised: 6 August 2022, accepted: 16 August 2022

Abstract. Liquefied petroleum gas (LPG) availability as a source of domestic fuel in the neighborhood is a touchy subject. If there is a shortage then chaos and inflation can occur. Households, and small business stands, which are end customers, are usually disloyal. To obtain the LPG, they are not restricted to a single store. Since the number of circulating tanks remains constant, analysis of LPG availability can be focused on the number of tanks. A continuous simulation method with system dynamics is generally used in system growth analysis. In this paper, a significantly smaller system made up of filling stations, agents, and other components is used to describe the discrete movement of tanks circulating in the community. The modeling results give a clear enough image of how the tank's availability can be suitably optimized.

Keywords: LPG distribustion, cylinder tanks, system dynamics, cyclic distribution system.

1. Introduction

Since 2007, kerosene has been replaced in Indonesia by liquefied petroleum gas (LPG), which is now a significant fuel for households and small-scale food businesses. Because the calorific value of LPG can improve savings by up to 10-15 percent compared to when using kerosene, public has welcomed the conversion of the use between the two types of fuel [1]. Tank-shaped containers are used to transport LPG. There are two sizes available for home needs: 3 kg and 12 kg. Its distribution to the population must run smoothly, especially for LPG in 3-kilogram tanks, which is subsidised LPG, to assure its availability. If the availability is disrupted, public panic may arise. The tanks will return to the LPG filling station (LFS) in stage: from households to stores, from stores to agents, and from agents to LFS. By focusing on the circular motion of the LPG containers, i.e., the tanks, this case constitutes a cyclical system. This is similar to the case of a production line where workpieces are placed on pallets [2], [3], [4].

Reverse manufacturing is a more general example, where some but not all of the material is sent back to the upstream. The phrase "reverse supply chain" is used in [5]. Ghisolfi et al [6] used system dynamics to describe the closed loop supply chain used in the manufacture and sale of personal computers in Brazil. Kamyabi et al [7] discusses closed-loop battery supply networks using system dynamics and mixed integer stochastic programming. The simplest variant of this problem, in which there is just one channel in each echelon, has been attempted to be discussed in [8]. One LFS, one agent, and one store make up the entire system. Additionally, [8] makes the assumption that customers only shop at one retailer and never visit another. The discussion is directed at the distribution of 3-kg LPG, which is contained in a green tank.

In real conditions, each echelon normally has more than one channel (multi-channel). Certain LPG filling stations (LFS) serve several agents who serve multiple stores. Furthermore, each store caters to many household consumers or micro-food stalls. This paper discusses the case of multi-channel where household consumers are disloyal. Specifically, household consumers are not tied to one store to buy their LPG. This situation is interesting because the assumptions are consistent with what happened. In this case, household consumers are end users who can only buy LPG from retail stores. The number of purchases by each end user is assumed to be only about one to two green tanks for each purchase. Purchases are accompanied by the exchange of an equal number of empty green tanks. The problem of distributing LPG in tanks is a case that occurs in a closed loop supply chain (CLSC).

Several methods can be used for the analysis of CLSC. Mathematical modeling is a fairly popular method in which the problem is expressed in an optimization formula, for example, mixed integer linear programming (MILP). Mashaei et al [4] discussed the case of a manufacturing system design using pallets using the MILP technique to optimize the number of pallets and was accompanied by the Colored Petri Net (CPN) method as a comparison, and [9] discussed a CLSC case using the MILP method, which was then solved by the concept of Lipschitz Continuity. Queue-based models, often called performance models, are often used to accommodate the dynamics of the states of the system [10].

The inflexibility of mathematical models makes simulation methods a widely used alternative for discrete-event simulation, agent-based modeling, system dynamics, or hybrid [11], [12], [13]. Continuous simulation using the concept of system dynamics is carried out by considering the entity as a fluid. In it, the real model is composed of a series of ordinal differential equations. The model obtained is very flexible and can accommodate many scenarios. The actual discrete system conditions can be recovered by using a time step of one unit of time. As a result, the assumption that the material is continuous can be revisited [14].

In this paper, the system dynamics method is preferred. With this method, several important factors in the system can be accommodated properly. Not only can system dynamics properly accommodate state dynamics, but feedback in the system can also be accommodated [15]. In addition, because it is actually a system of differential equations, system dynamics method does not require as much replication as discrete-event simulations, apart from the flexibility of the model obtained to be used in various variations of the value of the decision variables.

2. Description of the system under study

Figure 1 shows the conceptual scheme that occurs in the system under study. One LPG filling station, namely LFS, serves several LPG agents. Each agent serves several LPG stores and each store serves retail consumers. Each retail consumer has a random repurchase rate, as well as the amount purchased is also random. These retail consumers do not always buy LPG at the same store. There are times when they buy at other stores, which may be different agents/LFS. On the other hand, other consumers from outside the area around the store can also buy LPG at the store. In contrast to retail consumers, all stores and all agents in the system must be loyal to their suppliers.

3. Problem statement

For a prototype 3 kg LPG distribution system with multiagent (represented by two) and multistore (represented by two), the problem is formulated as the circulation of total number of 3 kg LPG tanks in the system so that LPG availability in the community is maintained. Since the number of tanks consists of filled and empty tanks, the total number of tanks does not necessarily reflect the amount of LPG in the community. The appearing questions are about what happens if the total number of tanks is too many or too few.

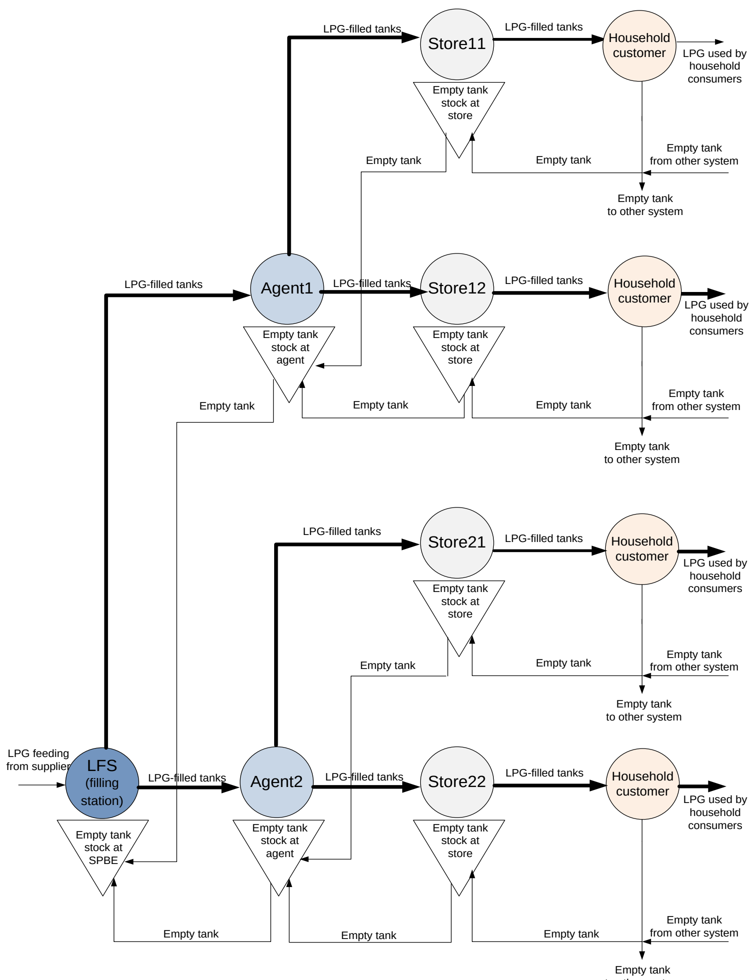

Figure 1. Conceptual diagram of the system under study: one filling station serves several (represented by two) agents, each agent serves several (represented by two) stores, and each store serves several (represented by one) disloyal household customers.

4. Modeling the LPG availability in the system

The continuous dynamical model is built by assuming that the system entity is a fluid. So, in this continuous model, there are level/stock variables and flow variables (inflows and outflows). In addition, in the model, there is also a third type of variable, which is an auxiliary variable that is useful for changing one variable to another. The whole thing is expressed in stock and flow diagrams.

4.1. Modeling multi channel dan proses cyclical

The physical diagram of the system (Figure 1) is shown in sections into each echelon in Figure 2, Figure 3, and Figure 4. There are two channels in each of these figures, which are intended to represent the multichannel in each echelon that actually occurs. The entity flows from upstream to downstream in the form of tanks containing LPG 3 kg, and from downstream to upstream in the form of empty tanks.

In Figure 2, the LFS echelon fills empty tanks taken from the stock of empty tanks ready to be filled with LPG to produce LPG-filled tanks that are accommodated in stock LPG-filled tanks. Furthermore, LPG-filled tanks are sent to each agent in batches according to their respective order quantity.

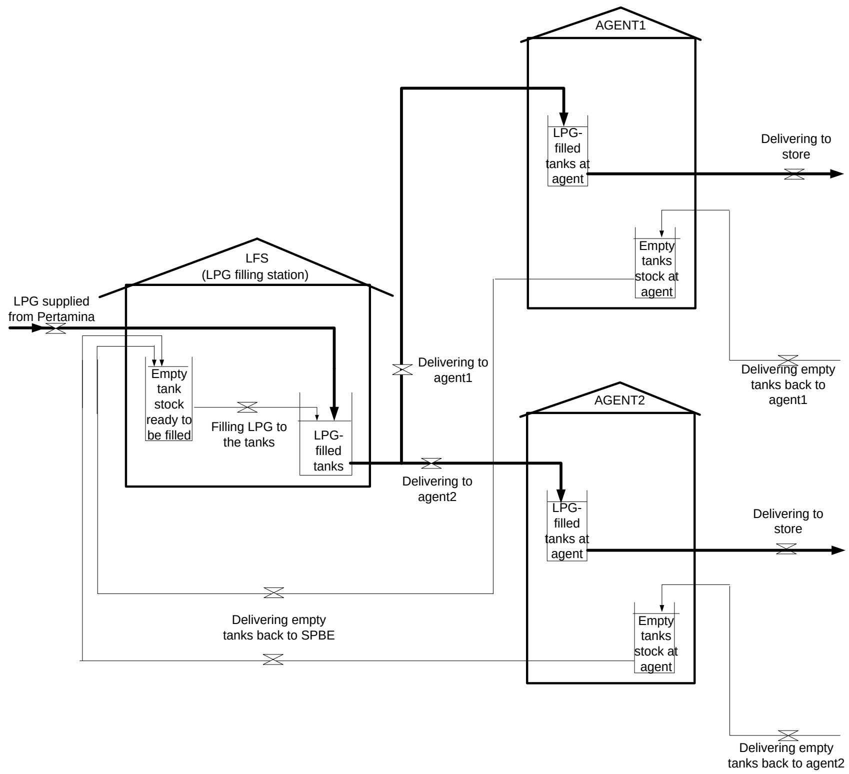

Figure 2. Physical diagram depicting a continuous model of the one LFS-two agents system.

Gas filling activities at LFS and delivery to agents are depicted by the symbol of a faucet or valve (⨝). Stock is symbolized with a container (□). The echelon is depicted with the symbol of home (⌂). By using the same symbol, the echelon of agents and stores can also be depicted in a physical diagram (Figure 3 and Figure 4). It can be seen that at the LFS echelon there are process activities (i.e., filling) and storage, while at the agent echelon or at the store echelon there are only storage activities. Moreover, in all echelons, there are storage tanks for contents and empty tanks. Retailer demand (from household customers) is symbolized with a circle (○). One large circle that is drawn actually represents many small circles, where each small circle represents a household customer. In this case, the store echelon serves many household customers. Figure 4 accommodates the possibility of disloyalty from end users as well as the possibility of purchasing by end users from other systems. Disloyalty causes the tanks to flow out of the system (to enter another system). On the other hand, when there is a purchase by the end user from another system (external disloyalty), then there is a flow of tanks coming in from the other system. Each retail transaction is assumed to only range from one to two LPG tanks.

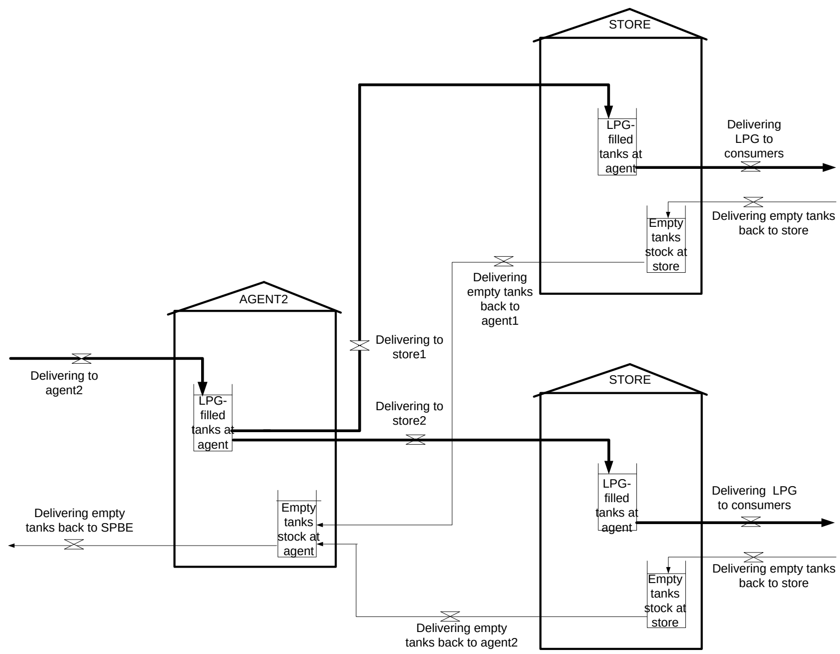

Figure 3. Physical diagram depicting a continuous model in one agent-two stores.

In this paper, the retail demand rate will be modeled hypothetically (without empirical data) into two random quantities, namely the time between arrivals of demand and the quantity purchased (in units of LPG tanks). Each is modeled with a specific theoretical probability distribution. For example, the distribution of time between arrivals is exponentially distributed, and the distribution of quantities purchased is modeled with a uniform distribution.

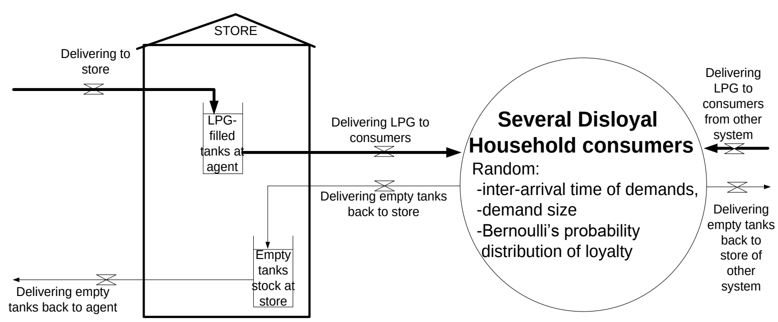

Figure 4. Physical diagram depicting a continuous model of one store-several disloyal customers.

The disloyalty of household customers is caused by the opportunistic behavior of these customers in obtaining their LPG. Every customer is not tied to the same store. That is, they can buy it from any store, depending on their situation at the time. The disloyalty in this paper will be modeled simply by the Bernoulli probability distribution.

4.2. Implementation of the model into stock and flow diagrams

The dynamics of the system are expressed in stock and flow diagrams, which in this paper are implemented with Vensim® PLE downloaded from https://vensim.com/free-download. In the stock and flow diagram, several auxiliary variables, flow variables, and additional level variables are added to accommodate the conditions for how the "fluid" flows from one stock to the next. Indrawati and Murdapa [14] provides a simple example of how flows and stocks need to be controlled with the addition of a number of auxiliary variables so that the model can reflect the behavior of the system.

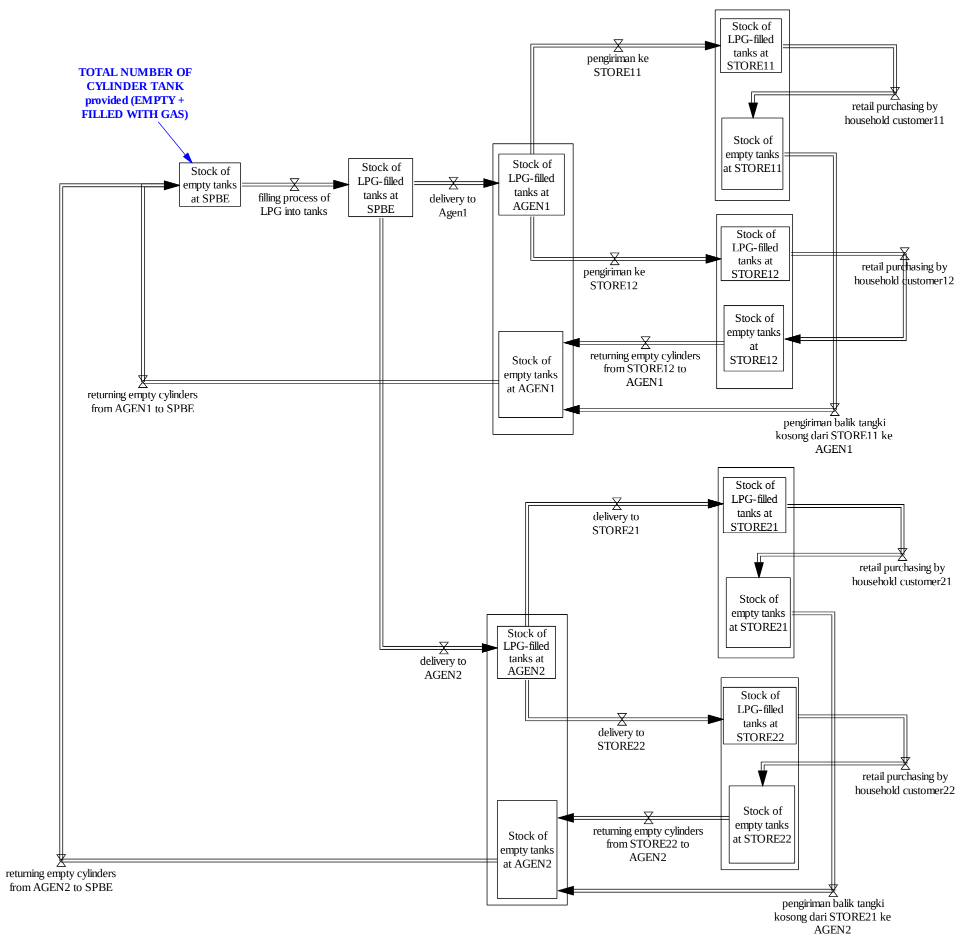

Figure 5. The overall SFD (incomplete) concept for the system under study

Figure 5 shows the SFD concept for the system under study to which activity control structures have not been added. The number of tanks in the system remains constant, because the purchase of LPG in tanks is always accompanied by the delivery of empty tanks. The LPG supply process occurs from upstream to downstream. It starts with filling the empty tank in LFS with the following mechanism: reproduction point r, and target stock R. Initially, all available tanks are only in the empty tank stock at LFS. Gradually the empty tanks are filled with LPG in the LFS so that the stock of tanks filled with LPG increased. However, several tanks will be sent to the agency, so the number of LPG-filled tanks decreases again. When the stock of LPG-filled tanks in LFS drops to equal or less than the reproduction point r, the filling process starts immediately, and stops when the stock has reached the target amount R. Next, the supply of LPG-filled tanks at the agent or in the shop follows the mechanism: reorder point R and order quantity Q. The stock of LPG-filled tanks at the agency is continuously monitored. When the level has been lowered to the reorder point level, the agent places an order to LFS for the specified order quantity. The filled tank will be directly sent by LFS to the agent with a certain lead time. Figure 6 below shows the stock and flow diagram.

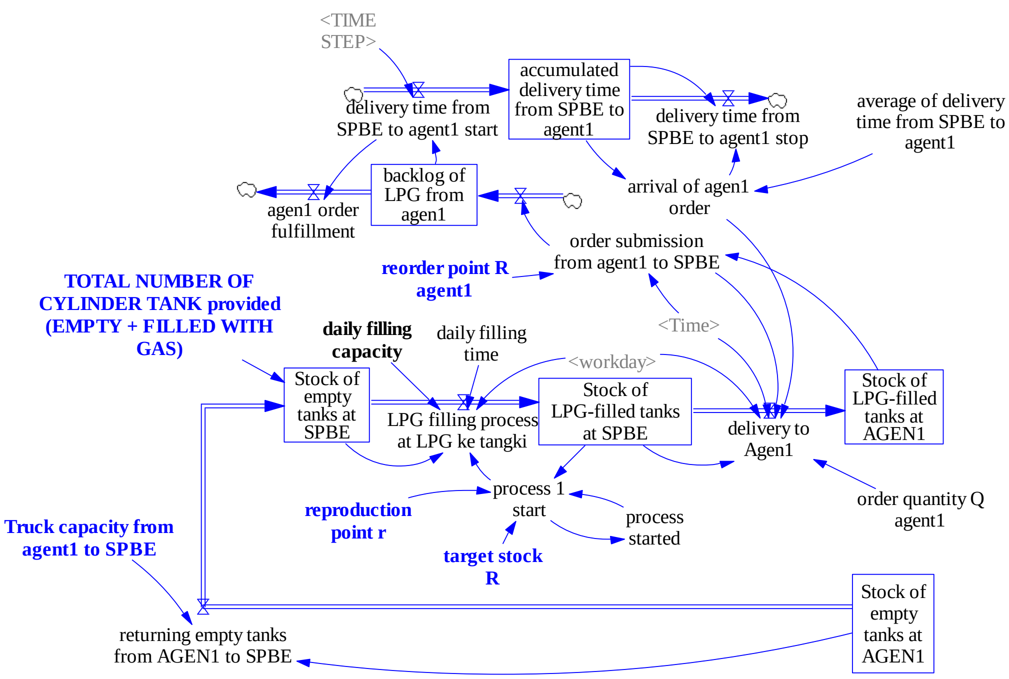

Figure 6. Stock and flow diagram of LPG filling process at LFS, ordering process from agent to LFS, and delivery leadtime process from LFS to agent

Figure 7 shows the process of ordering LPG from a store to an agent and the process of shipping the tanks from the agent to the store. The process of returning an empty tank occurs from downstream to upstream. The process starts with retail consumers (households) who buy 1-2 tanks of LPG from the store they prefer at that time. When they buy the LPG, they also by exchange empty tanks of the same amount. Empty tanks in the store are accumulated and sent periodically to agents with a certain sized fleet. Likewise, when empty tanks are collected at the agency, the tanks are sent to the LFS with a fleet of a certain capacity. Logically, the fleet from agents to LFS is larger than the fleet from stores to agents.

Demand from retail customers is random and is modeled by the Bernoulli mechanism. As an example, consider Store11, which is one of the downstream echelons of Agent1. First, a random number U(0,1) is generated. Suppose, the probability that a retail customer will be disloyal is p11 (that is, the probability that the final customer will buy LPG from outside the system), then the probability that a customer will buy LPG from a store within the system is 1- p11. Figure 8 shows the mechanism in the form of a stock and flow diagram, where the following equations are used.

$$bernoulli11 = random\,0\,1\,() \tag{1a}$$

$$disloyality\ customers11 = IF\ THEN\ ELSE(bernoulli11 >= p11, 1, 0) \tag{1b}$$

Here, *bernoulli*11 functions to bring up a purchase event at a time, from household customers to Store11, which is expressed by generating random numbers between 0 and 1 which are uniformly distributed (equation-1a). The number that appears is then compared with the probability of being disloyal to p_{11} (then the probability of being loyal is 1-p_{11}). Equation-1b is the random variate function to simulate the disloyalty event.

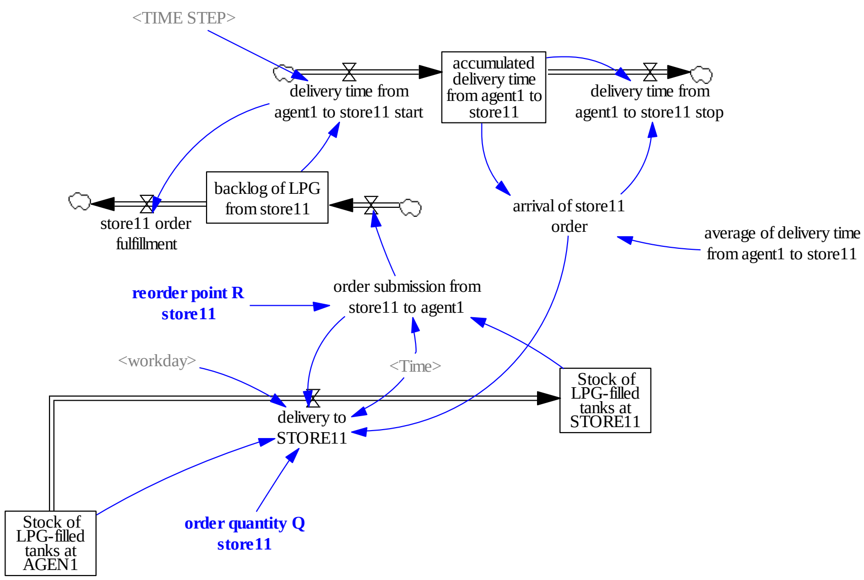

Figure 7. Process of delivery to agent, order from store to agent, delivery to store, leadtime from agent to store, and loyalty.

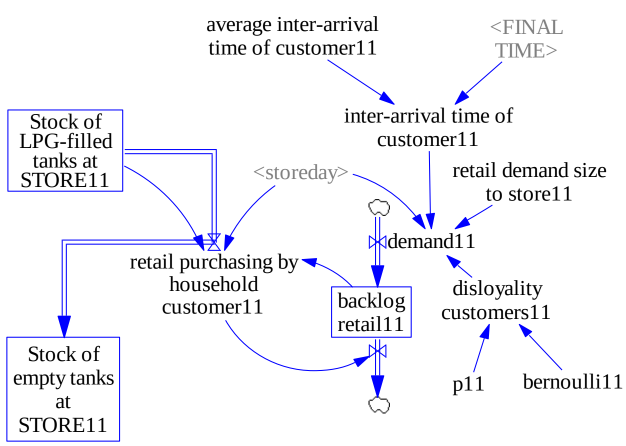

Figure 8. The retail buying process by the customer, disloyalty is modelled as the Bernoulli process.

On purchase, a customer pays by including the same number of empty tanks as the LPG-filled tanks purchased. The shop collects the empty tanks until they reach a certain amount before being sent to the agency in a small truck (Figure 9). Likewise, agents collect empty tanks from stores up to a certain amount and then transport them to LFS in a large truck.

Here, the working hours of LFS and agents are limited, for example, from 08.00 to 16.00, while a store, for example, may remain open until 20.00. Conversion from Time to Hours and Days is required. This is done using the function Modulo(a, b), where a is Time, and b is 24.

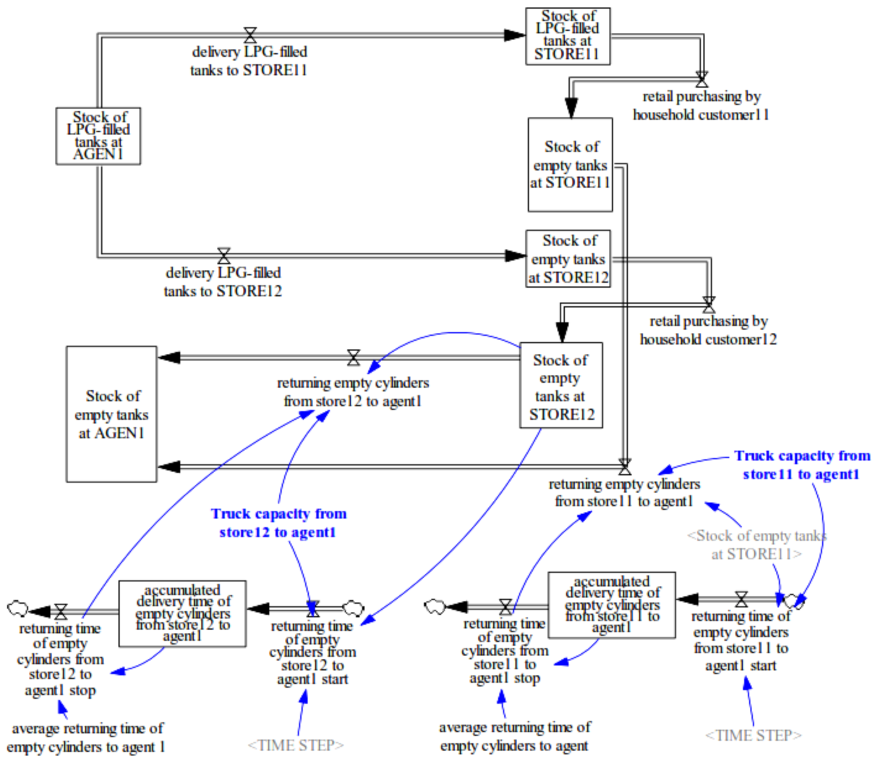

Figure 9. Process of collecting and returning empty tanks from store to agent (one agent – two stores).

4.3. Model verification

Since the case is hypothetical, model validation cannot be performed. On the other hand, the model can be verified by looking at its behavior under extreme conditions, i.e. when the number of tanks is 0 or at a sufficiently low value. If the number of circulating tanks in the system is less, the system activity should stop because one or more of the LPG-filled tanks is depleted. Figure 10 shows three conditions for the number of tanks, namely 500, 1500, and 2500 units, which result in very different levels of LPG tank stock at LFS. When the number of tanks is only 500 units, it is seen that the stock of LPG-filled tanks is very low, which is seen in some time slots when the stock is zero. This is very different from when the number of tanks was 2,500 units. The display illustrates that the model has been able to provide the logical trend, as it should.

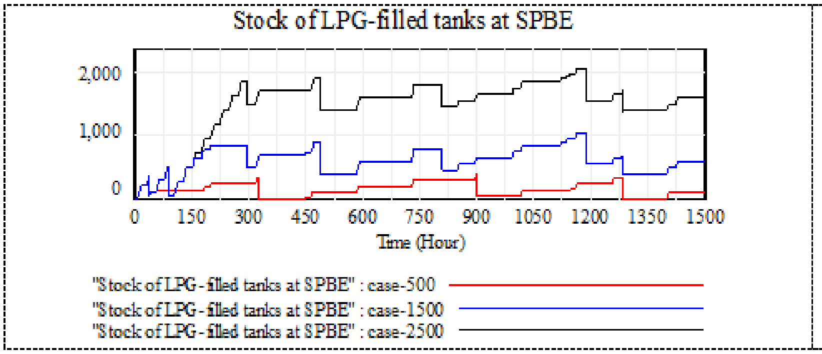

Figure 10. Comparison of two conditions with different numbers of circulating tanks, in their effect on the stock value of LPG-filled tanks at LFS (500 vs 1500 vs 2500)

5. Numerical example

As an example, consider the following hypothetical situation. Table 1 lists the cases' natural conditions, which are uncontrollable. Table 2 shows a list of control variables that represent controllable conditions. The uncontrollable natural quantities in Table 1 are determined primarily by the natural conditions that exist or surround the system under study. The values are frequently random (a random variable). Meanwhile, the quantities that the system manager has complete control over are referred to as control variables. Table 2 shows an example of a decision combination.

Table 1. Table 1. List of nature variables and examples of their values

No	Variable name	Type of variable	Value	Unit
1	daily filling capacity	Nature	200	Tanks/Day
2	daily filling time	Nature	8	Hours/Day
3	average of delivery time from LFS to Agent1	Nature	3	Hours
4	average of delivery time from LFS to Agent2	Nature	3	Hours
5	average of delivery time from Agent1 to Store11	Nature	1	Hours
6	average of delivery time from Agent1 to Store12	Nature	1	Hours
7	average of delivery time from Agent2 to Store21	Nature	1	Hours
8	average of delivery time from Agent2 to Store22	Nature	1	Hours
9	average returning time of empty cylinders from store11 to agent1	Nature	1	Hours
10	average returning time of empty cylinders from store12 to agent1	Nature	1	Hours
11	average returning time of empty cylinders from store21 to agent2	Nature	1	Hours
12	average returning time of empty cylinders from store22 to agent2	Nature	1	Hours
13	average returning time of empty cylinders from agent1 to LFS	Nature	3	Hours
14	average returning time of empty cylinders from agent2 to LFS	Nature	3	Hours
15	retail demand size to store11	Nature	Uniform(1, 2)	Tanks

No	Variable name	Type of variable	Value	Unit
16	inter-arrival time of customer11	Nature	Exponential(average inter-arrival time of customer11)	Hours
17	average inter-arrival time of customer11	Nature	4	Hours
18	retail demand size to store12	Nature	Uniform(1, 2)	Tanks
19	inter-arrival time of customer12	Nature	Exponential(average inter-arrival time of customer12)	Hours
20	average inter-arrival time of customer12	Nature	3	Hours
21	retail demand size to store21	Nature	Uniform(1, 2)	Tanks
22	inter-arrival time of customer21	Nature	Exponential(average Inter-arrival time of customer21)	Hours
23	average Inter-arrival time of customer21	Nature	4	Hours
24	retail demand size to store22	Nature	Uniform(1, 2)	Tanks
25	inter-arrival time of customer22	Nature	Exponential(average inter-arrival time of customer22)	Hours
26	average inter-arrival time of customer22	Nature	4	Hours

Table 2. List of decision variables and examples of their values

No	Variable name	Type of variable	Range of value	Unit
1	target stock R	Decision	3000	Tanks
2	reproduction point r	Decision	200	Tanks
3	reorder point of agent1, R_{Agent1}	Decision	125	Tanks
4	order quantity of agent1, Q_{Agent1}	Decision	500	Tanks
5	reorder point of agent2, R_{Agent2}	Decision	100	Tanks
6	order quantity of agent2, Q_{Agent2}	Decision	350	Tanks
7	reorder point of store11, $R_{Store11}$	Decision	10	Tanks
8	order quantity of store11, $Q_{Store11}$	Decision	40	Tanks
9	reorder point of store12, $R_{Store12}$	Decision	10	Tanks
10	order quantity of store12, $Q_{Store12}$	Decision	50	Tanks
11	reorder point of store21, $R_{Store21}$	Decision	10	Tanks
12	order quantity of store21, $Q_{Store21}$	Decision	30	Tanks
13	reorder point of store22, $R_{Store22}$	Decision	10	Tanks
14	order quantity of store22, $Q_{Store22}$	Decision	40	Tanks
15	Truck capacity from agent1 to LFS	Decision	100	Tanks
16	Truck capacity from agent2 to LFS	Decision	100	Tanks
17	Truck capacity from store11 to agent1	Decision	25	Tanks
18	Truck capacity from store12 to agent1	Decision	25	Tanks

No	Variable name	Type of variable	Range of value	Unit
19	Truck capacity from store21 to agent2	Decision	25	Tanks
20	Truck capacity from store22 to agent2	Decision	25	Tanks
21	total number of cylinder tanks circulating	Decision	500; 1500; 2500	Tanks

For those conditions shown in Table 1 and Table 2, the model gives the stock profile of tank filled or empty in LFS, Agent1, and Agent2.

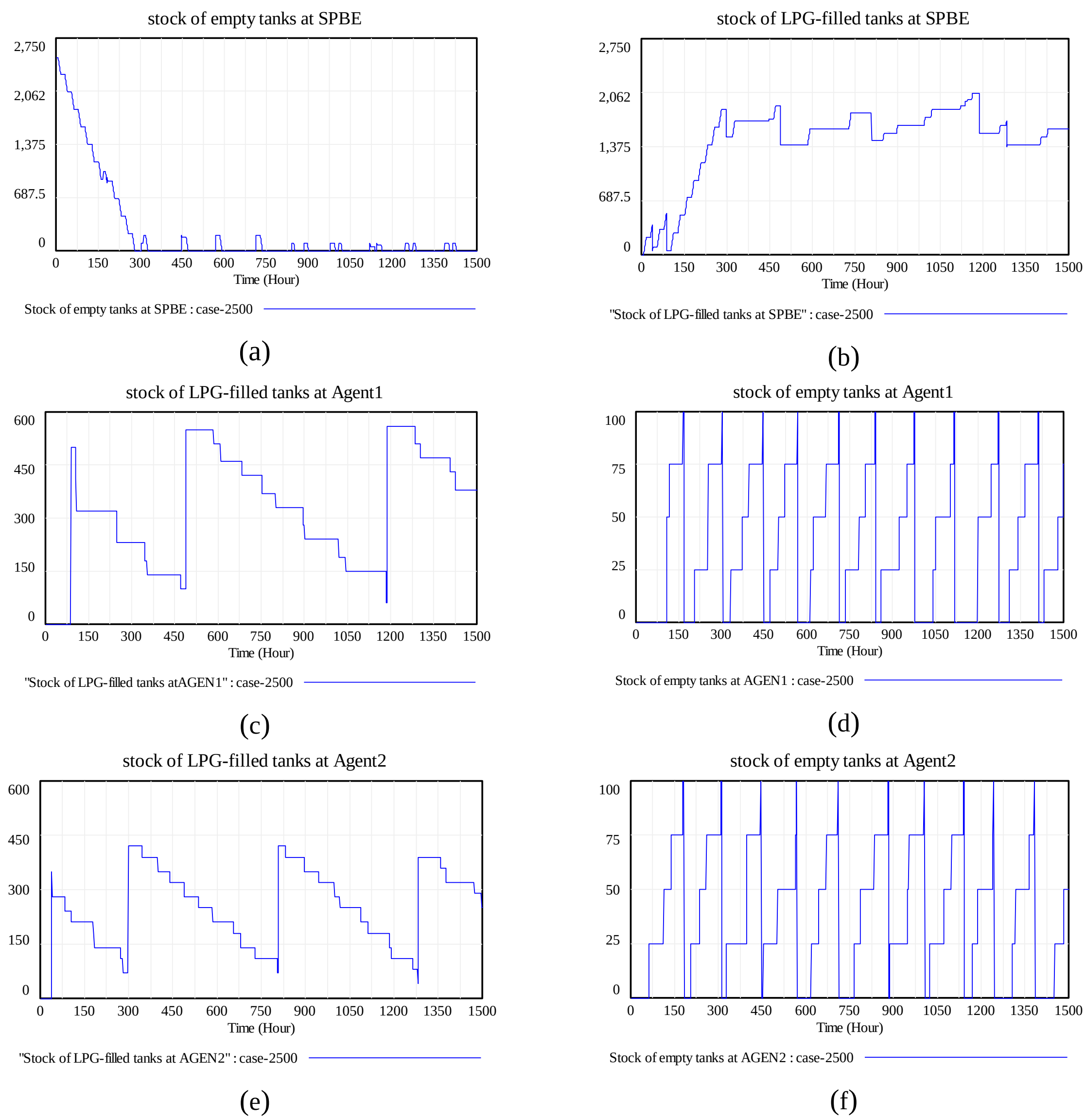

Figure 11. Profile of stock tanks filled or empty in LFS, Agent1, Agent2 when the number of circulating tanks is 2500.

Initially, all tanks are in stock of empty tanks at LFS. Seen at time = 0 the number of tanks is 2,500 (Figure 11a). After the LPG is filled into the tank, the tank then moves to the stock of filled tanks at the LFS. The tanks are then sent to agents: some to stock of filled tanks at Agent1 and partly to Agent2 according to their respective order quantities. From time = 300, conditions in the stock of filled tanks at LFS starts to be steady, where the stock level is between 1375 and 2062 (Figure 11b). Existing steep drops relate to dispatch events for Agent1 and Agent2. It can be seen that while the sharp decline occurred (Figure 11b), there was a spike in stock for Agent1 and Agent2 (Figures 11c and 11e). Meanwhile, the small spikes in Figure 11a correspond to the receipt of empty tanks from both agents. Delivery of empty tanks from an agent to an LFS occurs when the number has reached its maximum. It takes several hours to get to LFS.

6. Results and discussion

The set of differential equations is automatically attached invisibly to the stock and flow diagrams created in the software used, such as Vensim®. This will ensure that the material balance (in the case under discussion: tanks balance) along the supply chain will be properly accommodated through the use of the system dynamics language. When compared to other analytical techniques, this is a benefit.

The number of tanks (either filled or empty) currently in trucks is still disregarded in this analysis, while the truck's current lead time to its destination has been taken into account. This means that throughout the lead period, the number of tanks in each stock of filled or empty tanks will not vary. Since the lead time is relatively very short compared to the whole process, the waiver may be acceptable. Tank accommodation in trucks is accomplished by integrating vehicles into stock and flow. The truck is imagined as a vessel through which the tank will also flow.

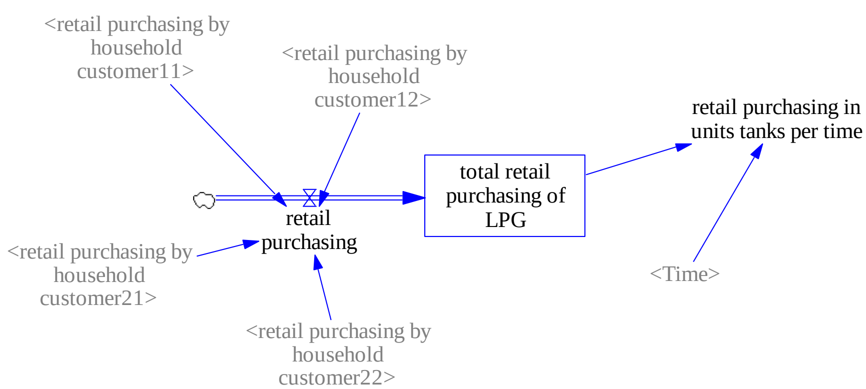

Figure 12. Calculation of total retail purchasing in units tanks per time.

An examination of the number of 3-kilogram tanks that should be circulated in the system (which can be extended to the community context) may be done using the system dynamics model that was constructed. In terms of the economy, reduced availability might lead to inflation. Meanwhile, supply inefficiency will happen if the availability is too high.

A response variable that may describe the efficiency of the number of circulation tanks must be developed. This study employs the response variable, the quantity of retail purchases made per unit of time, which is depicted in Figure 12 and specified by equation 2. An extremely big (extreme) number can be examined to determine how many tanks should circulate in the system. The number of tanks circulated in actual operation must be less than this extreme figure.

$$\text{retail purchasing in units tanks per time} = \frac{\text{total retail purchasing of LPG}}{\text{time of simulation}} \quad (2)$$

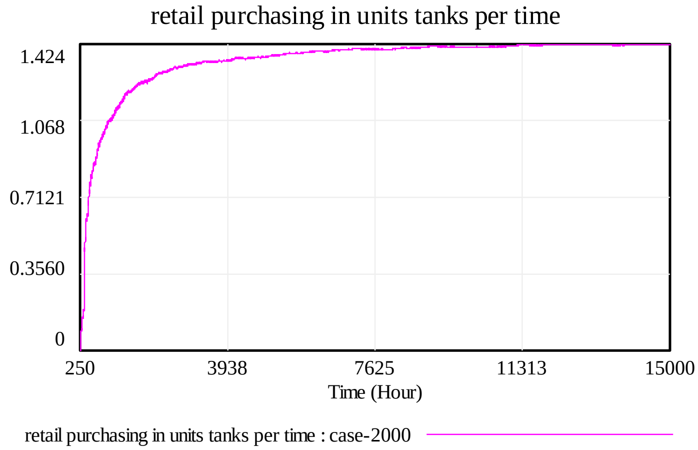

Figure 13. Calculation of total retail purchasing in units tanks per time.

After running the simulation for 15,000 hours, if many circulating tanks that has values 2,000, are selected, the resulting retail purchase in tank units is approximately 1,424 tanks/time (Figure 13). The number 2,000 might be too high. For testing, we can put the system at a lower value that still provides the same performance and then run a fewer number.

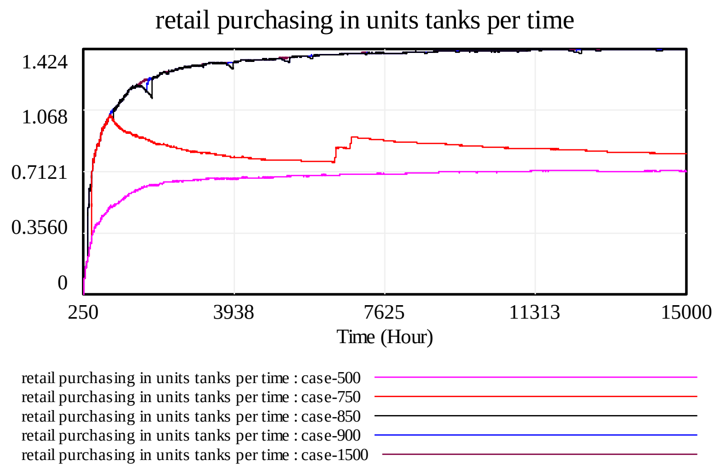

Figure 14. Calculation of total retail purchasing in units tanks per time.

Figure 14 displays the profiles of retail purchases made at a certain number of circulating tanks in tank units per time (500, 750, 850, 900, 1,500). It is evident that a system with 1500 circulating tanks can perform at a level equal to that of a system with 2,000 tanks (and at values of 850 to 900, it still looks good). However, below the value of 750, the system's effectiveness drastically declines due to stock shortages in various levels.

A real-world application will be influenced by a number of variables, including the number of household customers, the rate of LPG usage per customer, the capacity of the LFS, the capacity of the trucks (and their reliability, which is assumed to be 100% in this paper), the lead time for delivery, the number of agents, and the number of stores per agent.

7. Conclusion

LPG is delivered in tanks for use in local economic activities. Subsidized LPG is sold in green, 3 kg tanks in Indonesia. To maintain the calmness of society, LPG must be made available. There will always be the same number of circulating tanks, both filled and empty, because people can only purchase LPG in tanks by giving over the same number of empty tanks. Using continuous simulation, also known as the system dynamics method, it is possible to assess the number of empty tanks accurately in accordance with the level of community demands. The quantity of LPG can be determined for a specific system (community) situation (in units of LPG-filled tanks). A more real application and research in the wider community can be carried out to obtain the application of methods that are more in line with the actual behavior of nature in the community.

8. Acknowledgement

The author would like to thank for the support and great discussion from the academics of the Widya Mandala Catholic University Surabaya, and Sepuluh Nopember Institute of Technology (ITS) Surabaya.

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