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Simulation-Based Education in Supply Chain and Project Management

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Abstract Simulation-Based Education is part of the new teaching methods that have emerged over the past century, implemented in a variety of domains, and growing constantly ever since. It is an effective and dynamic educational tool that offers several advantages over traditional educations techniques. We have designed two state-of-the-art simulators, one within the supply chain management domain and the other within the project management domain. Both of these domains are of major concerns in operations management. This tutorial demonstrates the use of these simulators as a teaching tool and as a decision support system. Using the Supply Chain Simulator we show how it can be used to demonstrate the importance of using inventory position and not local inventory (net inventory) in the presence of lead times. Using the Project Team Builder we demonstrate the issues that need to be managed when trying to develop a project plan that minimizes the project cost while ending the project on or before a given due date and satisfying all the requirements.

Keywords simulation-based training; simulation-based education; project management; supply chain management

1. Introduction

Simulation is as old as mankind.

The hypothesis that simulation evolved with mankind is presented by Revonsuo [23, p. 877]. He postulates that the true purpose of dreaming is to perform a simulation. Indeed, in his view the brain is an expert simulation designer, since, according to him "...during dreaming, the brain constructs a complex model of the world in which certain types of elements, when compared to waking life, are underrepresented whereas others are over represented." As any good modern computer simulation designer knows, it is foolhardy to try to truly represent the real world. This maxim was best explained by Hari Seldon (one of Isaac Asimov's characters) when he stated, "If you want to understand some aspect of the Universe, it helps if you simplify it as much as possible and include only those properties and characteristics that are essential to understanding. If you want to determine how an object drops, you don't concern yourself with whether it is new or old, is red or green, or has an odor or not. You eliminate those things and thus do not needlessly complicate matters. The simplification you can call a model or a simulation and you can present it either as an actual representation on a computer screen or as a mathematical relationship" (Asimov [1, Chapter 7]).

This tutorial demonstrates two computer-based simulation tools, which on the one hand represent reality but on the other hand takes what we feel is important from reality for the user and emphasizes it beyond what is truly realistic. In §2 we present the Supply Chain Simulator (SCS), which is a representation of the periodic review inventory paradigm; and in §3 we present the Project Team Builder (PTB) that can simulate any kind of project.

These two simulators, both intended for engineering and management education, are part of a growth in new teaching methods that have emerged over the past century. These methods have utilized pedagogical approaches that include frontal lectures, books, recorded presentations, seminars, group learning, etc. Being confined to a classroom environment, traditional methods have struggled to translate expert intuition and theoretical knowledge into practical experience. An emulation of a real physical environment, indeed a simulation, is one way to give new life to education. Implementing this emulation efficiently and effectively, however, is challenging (see, e.g., Doulgeri and Zikos [9], Gunes and Baba [12], Heuer [13], and Leemkuil and De Jong [17]).

Simulation has been extensively used in education and in particular computerized automated simulators have been used in this way. Simulation creates an artificial environment that reflects and illustrates real-life experiences (Bell et al. [3]). Simulation can even replace physical experiments without compromising student learning (Wiesner and Lan [26]).

Students acquire needed knowledge during their experience with the artificial environment (simulation) and the subsequent implementation of this knowledge, again in the simulation. One characteristic of an efficient simulation tool is its ability to facilitate learning that can be transferred to a real-life environment (Thompson and Bergus [25]). In the context of education, using simulation as a teaching methodology is commonly referred to as simulation-based training (SBT). In particular, we are interested in computer-based simulations.

SBT is an effective and dynamic educational tool as described in Salas et al. [24]. The effectiveness of SBT has been widely studied, not always in a positive light (see, e.g., Bangert-Drowns et al. [2], De Jong and Van Joolingen [8], and Gunes and Baba [12]). Nonetheless, many educators support the use of SBT techniques (Fraser et al. [10], Grimes and Willey [11], Kumar and Labib [16], Zantow et al. [27]) as they enable students to practice what they are studying (Hoheisel et al. [14]). Simulators can provide an attractive, novel, and entertaining environment so trainees are motivated to practice (Koh et al. [15]). Students are more engaged in what they are learning when they use SBT (Coller and Shernoff [5]).

Using SBT for education offers several advantages over traditional techniques, such as supplying hands-on practice and allowing for the development of skills at a faster pace (Salas et al. [24]). Another advantage of SBT is it provides an environment that is risk free, i.e., mistakes can be made without anyone having to suffer the negative repercussions. Indeed, we have repeatedly lost considerable money managing a supply chain with the SCS and no one has cared. Of course, losing money is not the point; learning is. If the simulators are properly designed and used, SBT makes the learning process effective.

We are interested in using simulators for two separate but related purposes. The first is to use simulation for knowledge transfer and the second is to use simulation to build knowledge. We illustrate each of these with an example from the SCS.

To understand how the SCS can be used for knowledge transfer, consider the classroom concept of when an entity in the supply chain should place a replenishment order. More specifically, consider on what basis an entity should place such an order. One possibility is to consider the on-hand inventory. This is the easiest, but it is clearly suboptimal for several reasons. For instance, when there is a (long) replenishment lead time, net inventory position is clearly a better choice. Moreover, when considering a multiechelon environment, the downstream inventory (echelon inventory) must also be considered. Whereas these concepts are well understood by the instructor, transferring this knowledge to students can be difficult. This is especially true using only frontal lectures. Students cannot fully appreciate these concepts until they "see" and "feel" them. This is where the SCS comes in. Through a series of well-structured exercises and through some unstructured "play" time, the student can build an understanding of the concept that goes beyond knowing the correct answer.

To understand how the SCS can be used to build knowledge and is not limited to transferring knowledge, we must consider a nonstandard supply chain concept. Consider, for example, inventory discrepancies. Even though the presence of discrepancies in inventory records is obvious—indeed, this is the motivation for inventory counts—their effect on the supply chain performance has only recently gained attention. Computer-based simulation tools, such as the SCS, can help researchers build an understanding of this phenomenon. By investigating systems that simulate the sources of inventory discrepancies (shrinkage, misplacement, and wrong scanning), the researcher can build hypotheses that can be tested via simulation and can be rigorously verified using mathematical models.

To close the introduction, we return to Revonsuo's [23, p. 882] hypothesis. He states that "dream consciousness is essentially a mechanism for simulating threat perception and rehearsing threat-avoidance responses and behaviors." This is exactly what we feel that the two simulators do for students while they are awake.

2. The Supply Chain Simulator

The Supply Chain Simulator is a Web-based computer simulation application developed at the Technion. It is an educational platform whose goal is to enable students to gain a better understanding of supply chain management by providing a virtual environment for the student to experience managing supply chains. Students must simultaneously consider diverse aspects such as costs, ordering policies, transportation modes, capacity, and uncertainty. Students must also manage multiple (often conflicting) goals such as minimizing costs and maximizing service levels. The SCS is based on the following principles:

(a) *Ease of use.* An intuitive and friendly graphical user interface (GUI) is designed to support intuitive actions with no need for prior knowledge or extensive practice, even though the simulator itself is an advanced and sophisticated tool.

(b) *Scenario-based training.* Each exercise on the SCS is a well-prepared scenario combining a detailed case study and specific instructions regarding the exercise's goals. The GUI and the data encourage the trainee to accomplish the specific assignments.

(c) *Flexibility.* The SCS enables the modeling of deterministic as well as stochastic environments. Several standard and nonstandard costs can be incorporated. Supply chain entities can be linked either serially, as a tree, or even with cycles. Several supply modalities are available including different transportation modes and even transshipments.

(d) *Supportive data.* Supportive data-driven and comprehensive detailed reports facilitate the trainee's decision making and coping with the scenarios' dynamic states.

The SCS provides an advanced and enjoyable environment for training by enabling the simulation of a large variety of realistic and pragmatic situations. Advanced users can even design and develop supply chain scenarios based on real or imaginary situations. The teacher can build an unlimited number of scenarios. Each scenario can consist of different entities representing supply chain facilities such as manufacturers, warehouses, and retailers.

2.1. The SCS Environment

The SCS allows one to model an extremely general discrete time supply chain model with a very simple tool. Conceptually, the SCS is based on entities that interact with each other. These entities can be a manufacturer, warehouse, or retailer. In general, each entity can receive products (from another entity or from production), store products, and distribute products (to another entity or to customers). The entities are linked by transportation routes that allow the flow of products from one entity to another. As this description implies, the system can be represented as a graph where the nodes are the entities and the arcs are the transportation links. In this graph we allow multiple arcs between entities, with each arc representing a different transportation mode.

The models built with the SCS are discrete time models. Seeing that the transportation of products takes time, products cannot arrive and depart from an entity in the same period. Lead times, i.e., the amount of time between products departing from an entity until they arrive at an entity, can easily be included in supply chain models. Indeed, both deterministic and stochastic lead times are available. Standard lead time distributions are built into the SCS. For faster (emergency) transfer of products, transshipment connections between the entities can be built into the model. In this way, products to be transferred between entities so that unmet demand in a given period can be met by products at another entity in the *same* period.

The products represented in the SCS can have either discrete or continuous quantities, and the demand for the products can be either deterministic or stochastic. Again, standard demand distributions (both discrete and continuous) are built into the SCS.

The basic decisions to be made in the SCS once a model is built are when and how much to order from what entity (or to produce) using what transportation mode. These decisions can be made manually by the user during the simulation or automatically. To facilitate learning, the standard ordering policies have been built into the SCS. In addition, there are decisions that can be made at the time of building the model—for example, how many levels to put into the distribution chain and where to place warehouses.

In addition to the basic decisions, more advanced models sometimes require additional decisions. For example, in the case of a limited number of products being in inventory, should priority be given to customers or to orders from other entities? Moreover, there are decisions to be made when building the model, e.g., where to locate a warehouse.

The user can make decisions based on what is important. The SCS measures both standard service-level metrics and costs. Costs are incurred whenever items are procured, transported (with the cost depending on the transportation mode), or held in inventory. In addition, unmet demand can be either lost or backlogged, with the appropriate costs. All costs can have both a fixed and variable (linear in quantity) component.

Another advanced supply chain concept built into the SCS's capabilities is the notion of inventory discrepancies. The three basic sources of inventory discrepancies (shrinkage, wrong scanning, and misplacement) and their effect on the ordering policy (the use of inventory records instead of available inventory) are features of the SCS. Similarly, the correction of the discrepancies if an inventory count takes place is included in the SCS.

Just as important to what the SCS does is what it does not do. Currently, the SCS has no optimization capabilities. The idea is to allow the user to experience a "real-world" supply chain and experience the consequences of both good and bad decisions.

Questions that can be explored using the simulator include the following:

- What are the differences and consequences of ordering based on local inventory, inventory position, echelon inventory, or echelon inventory position?
- Where should a warehouse be located?
- When should a shipment be made by air and when by sea?
- What is the effect of installing a local warehouse?
- How should we design a supply chain strategy for a system that includes dozens of entities?

2.2. Exercise 1. Local Inventory vs. Inventory Position

In this section we describe one of many possible exercises that can be built with the help of SCS to demonstrate supply chain concepts. Here, we demonstrate to the user the importance of using inventory position over using local inventory (net inventory) in the presence of lead times. Recall that orders based on inventory position consider not only the goods on hand (net inventory) but also the goods that have been ordered. We do this in a stochastic periodic review setting in which unsatisfied demand is backordered and the planning horizon is infinite.

2.2.1. Context. In this exercise, we have a supply chain that includes three entities: a manufacturer and two suppliers. See Figure 1. Retailer A and Retailer B face identical (in distribution) external demand. In particular, the demand at each retailers is normally distributed with a mean μ of 100 units and a standard deviation of 5 units. Manufacturer A has no external demand and supplies both Retailers A and B. The two retailers have the

Figure 1. Map of entities inside the SLS.

same attributes: the shortage cost, p, is equal to \$1 per unit per period and the holding cost, h, is equal to \$1 per unit per period. Since unsatisfied demand is backordered and the planning horizon is infinite, both the purchase cost and selling price are not relevant to understanding the difference between the two policies. However, to get logical results, we will set the purchase cost, c, equal to \$1 per unit and the selling price, V, equal to \$3 per unit. There is no fixed ordering cost. A fixed lead time, l, of four time periods is needed to supply a retailer from Manufacturer A by truck. Retailer A orders based on its local inventory (net inventory) whereas Retailer B orders based on net inventory position. There are 1,000 periods per simulation. The seed is equal to 4. We will focus on the profit and inventory states of the two retailers. To do so, we have to first determine the ordering policy for each retailer.

2.2.2. Ordering Policy. To be able to compare the results of the two retailers (i.e., the two ordering policies), we have to first determine their ordering policies.

Since Retailer B orders based on net inventory position its optimal ordering policy is well known. In particular it is a base stock policy that orders a quantity such that its net inventory position will be equal to $S_B = (l+1)\mu = 500$. Note that the demand standard deviation does not play a role in the optimal ordering policy. This is by design and was the motivation for us choosing the problem parameters such that $p = h$.

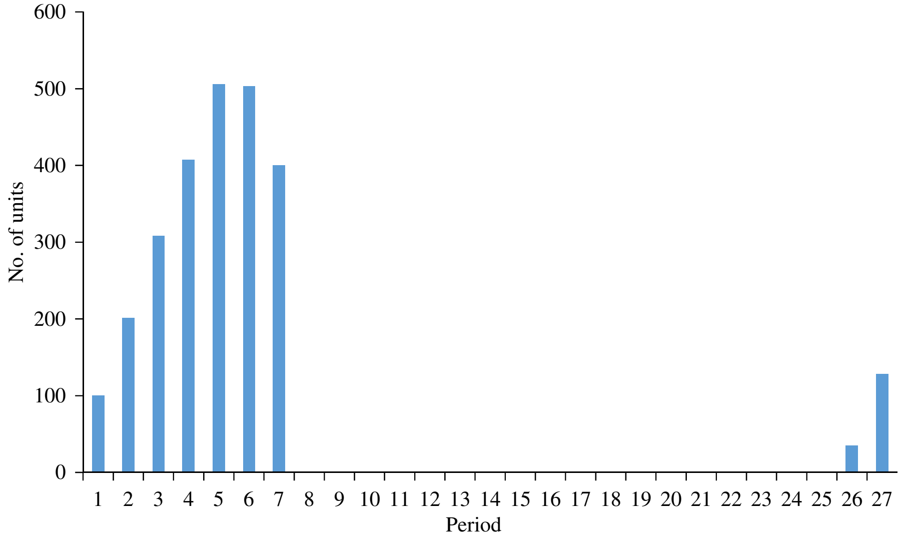
Retailer A is comparable to a newsvendor problem and uses a base stock with $S_A = \mu = 100$. Whereas this may not be the optimal policy, it is the most reasonable policy considering that the retailer is using local inventory. More importantly, the results below remain qualitatively the same no matter what base stock level is used.

2.2.3. Results. At this point you should run this scenario and observe the results. It should be clear that Retailer B's policy based on net inventory position is superior to Retailer A's policy based on net inventory. Indeed, Retailer B's profit is positive, whereas Retailer A's profit is negative. As both Retailer A and Retailer B have the same external demand with the same costs, we conclude Retailer A manages inventory less efficiency than Retailer B.

Retailer A. To understand why Retailer A's profit is so low, we first have to understand how the simulator makes an order at an arbitrary time period, t.

- Retailer A computes its net inventory, which is denoted by I_A.
- Retailer A places an order with Manufacturer A for $S_A - I_A$ units.
- Retailer A receives the order it placed in time $t - l$.
- Retailer A satisfies its backorders and then its demand in period t.

Figure 2. Orders at Retailer A.



One can go to the results section of the simulator (located under the map in the simulation but not shown here) and select total shortage cost in the first drop-down box on the left-hand side of the screen. Since $p = \$1$, the average shortage cost per period is equal to the average number of backorders per period. As $l = 4$ periods, the demand in the first four periods is backordered. In the first period, the retailer orders 100 units. In the second period, its net inventory is negative since there was unsatisfied demand in period 1. Thus in the second period around 200 units are ordered, in the third period approximately 300 units are ordered, and in the fourth period approximately 400 units are ordered. From period 5 through period 8, Retailer A receives its orders from periods 1 to 4, respectively. Consequently, the order quantity at Retailer A subsequently decreases. Since enough inventory is now on the way, the retailer does not order again until period 26. At this time, the backorders and the order quantities both start increasing again. See Figures 2 and 3.

Figure 3. Backorders at Retailer A.

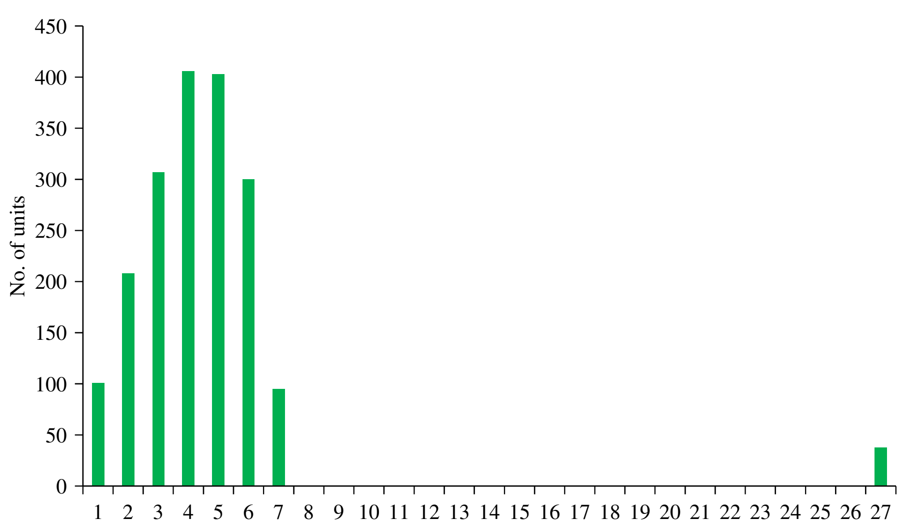
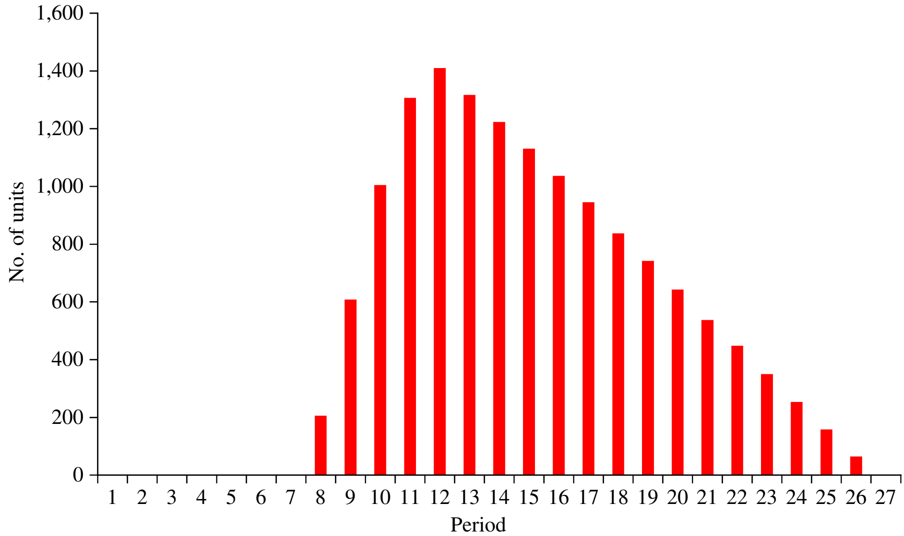


Figure 4. Inventory on hand at Retailer A.



Now that we have discussed the shortage costs, we can examine the holding cost by choosing total holding cost in the drop-down box in the results section of the simulator. Retailer A does not hold inventory during the first seven periods since period 8 is when it clears its backorders, as explained above. From periods 8 through 12, Retailer A receives its orders from periods 4 to 8, respectively. As there are no backorders anymore, and the orders in periods 5 to 8 were significantly larger than 100, the inventory starts to accumulate. From periods 13 through 26, the inventory decreases by 100 (on average, each period) because of the external demand. See Figure 4.

Finally, at time period 26, the inventory is depleted (plus or minus a few units because of demand fluctuation), and the situation is essentially equivalent to the one at time 0. Thus the system has a wave of orders (and backorders) followed by a wave of inventory every 26 periods. See Figure 5. The effect of this phenomenon on the total cost for Retailer A is straightforward. As $p = h = 1$, Retailer A's total cost is the area of both the red and blue "triangles" in Figure 5.

Retailer B. The simulator calculates order quantities for Retailer B in the same way it calculates order quantities for Retailer A with one important difference. Whereas the

Figure 5. Periodicity of orders and inventory.

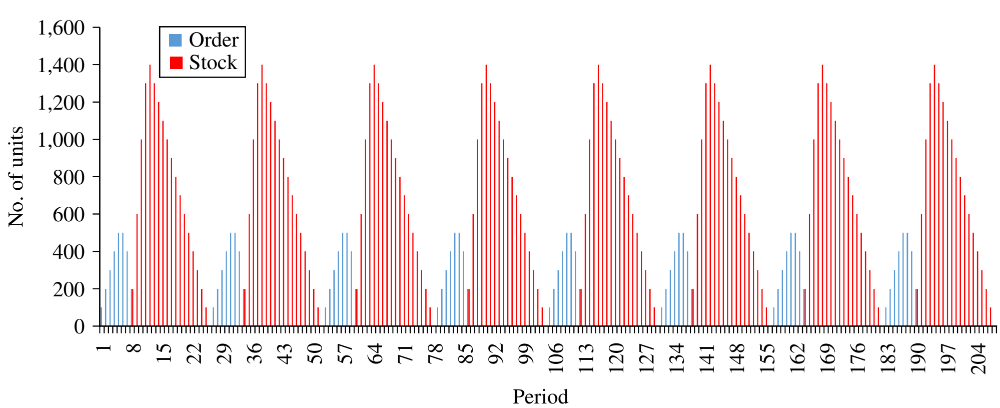
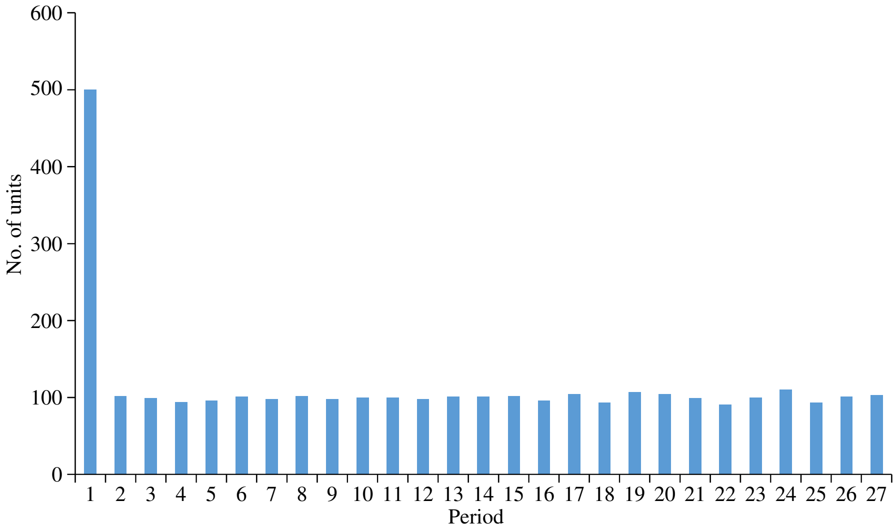


Figure 6. Orders at Retailer B.



simulator calculates the inventory for Retailer A based on its net inventory, it calculates the inventory for Retailer B, I_B, based on net inventory position, i.e., the number of units in the warehouse plus the number of units on order minus the number of backorders.

We can refer to the results section of the simulator (located under the map in the simulator but not shown here) and select total shortage cost in the first drop-down box on the left-hand side of the screen. For the four first periods, the situation is similar to that of Retailer A in terms of the number of backorders, but the orders are very different. Because of the inventory position policy, the first order is for 500 units (the initial net inventory position is zero). Thereafter, Retailer B orders enough to bring its net inventory position back to 500 units. This order quantity is exactly equal to the demand from the previous period. See Figure 6. In this way, the net inventory position is maintained at 500 after each order, but most of this inventory is in transit at the end of each period. On average, 100 units arrive each period to meet the average demand of 100 units. Of course, because of demand fluctuation, there is sometimes excess inventory and sometimes shortages. To see this, we can select total holding cost in the results drop-down menu in the simulator: the quantity of products in the warehouse is stable after the first four periods and remains around 0. See Figure 7. Be sure to note the difference in scale of the vertical axes between Figures 4 and 7.

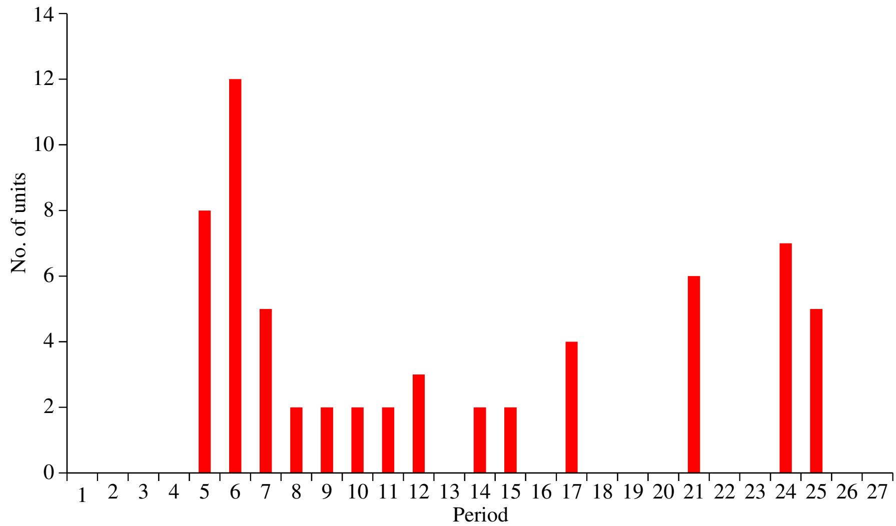
Until period 4, the shortage cost for Retailer B is similar to that of Retailer A. See Figure 8. However, Retailer B clears all of its backorders in period 5. Thereafter its holding and shortage costs are negligible compared to those of Retailer A. See Figures 7 and 8, again noting the scales of the vertical axes. Observe that the total cost of Retailer B is significantly smaller than that of Retailer A. Because the sales are similar for both retailers, Retailer B makes considerably more profit than Retailer A.

2.3. Exercise 2: Local Inventory vs. Inventory Position with Fixed Ordering Cost

In this section we describe an additional exercise that can be considered as a continuation of Exercise 1. Its main purpose is to show that the behavior described in Exercise 1 continues in related contexts. In the case of Exercise 2, the generalization is the presence of fixed ordering costs and nonidentical holding and shortage costs.

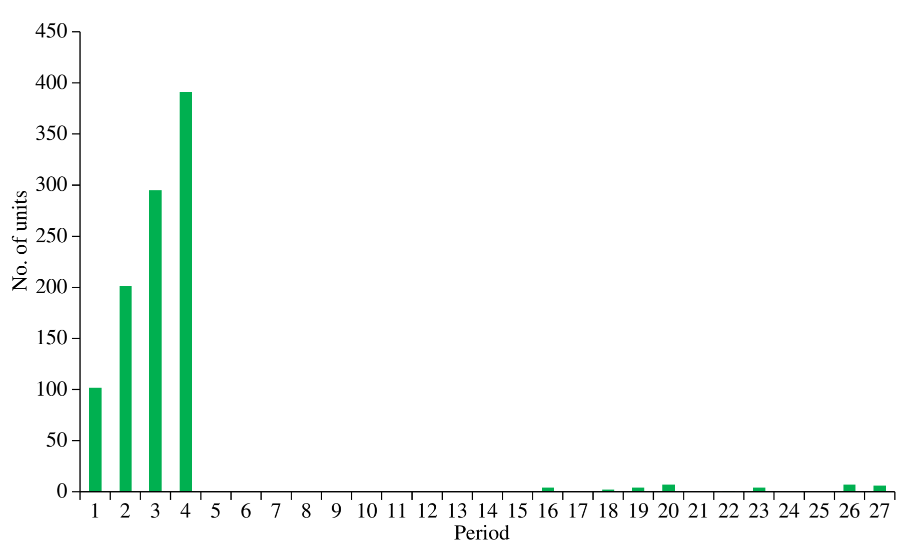
2.3.1. Context. In this exercise, we have a supply chain that includes three entities: a manufacturer and two suppliers. See Figure 1. Retailer A and Retailer B face identical

Figure 7. Inventory on hand at Retailer B.



(in distribution) external demand. In particular, the demand at each retailers is normally distributed with a mean demand of 100 units and a standard deviation of 5 units. Manufacturer A has no external demand and supplies both Retailers A and B. The two retailers have the same attributes: the shortage cost p is equal to \$6 per unit per period and the holding cost h is equal to \$1 per unit per period. Since unsatisfied demand is backordered and the planning horizon is infinite, both the purchase cost and selling price are not relevant to understanding the difference between the two policies. However, to get logical results, we will set the purchase cost c equal to \$1 per unit and the selling price V equal to \$10 per unit. The fixed ordering cost is \$300 per order. A fixed lead time l of four time periods is needed to supply a retailer from Manufacturer A by truck. Retailer A orders based on its local inventory (net inventory) whereas Retailer B orders based on net inventory position. There are 1,000 periods per simulation. The seed is equal to 4. We will focus on the profit and inventory states of the two retailers. To do so, we have to first determine the ordering policy for each retailer.

Figure 8. Backorders at Retailer B.



2.3.2. Ordering Policy. To be able to compare the results of the two retailers (i.e., the two ordering policies), we have to first determine their ordering policies.

As we face an infinite horizon stochastic lot-sizing problem with fixed ordering costs, we will use an (s, S) policy. That is to say, each time the inventory is less than s we order up to S. Moreover, since p is considerably greater than h, we view shortages as being a rare event. We will estimate the parameters s and S through a mapping to the continuous time analogue of this problem. In the continuous time version we have a (Q, R) policy; i.e., we order Q units every time each time the inventory reaches R units. The analogy is completed by setting $s = R$ and $S = R + Q$. See Nahmias [19] for details.

Since Retailer A only considers local net inventory, we have

$$\begin{cases} \mu = 100, \\ \sigma = 5, \\ \lambda = 20 \text{ units of product/unit of time,} \end{cases}$$

where λ is the demand rate. After solving for the two control parameters, we obtain $s_A = 99$ and $S_A = 209$.

For Retailer B, we have

$$\begin{cases} \mu = 500, \\ \sigma = 5\sqrt{5}, \\ \lambda = 100 \text{ units of product/unit of time.} \end{cases}$$

After solving for the two control parameters, we obtain $s_B = 515$ and $S_B = 760$. We note that the solution found through this approximation is not very good. This is because the value of Q in the (Q, R) policy is 245, which is enough for 2.45 periods.

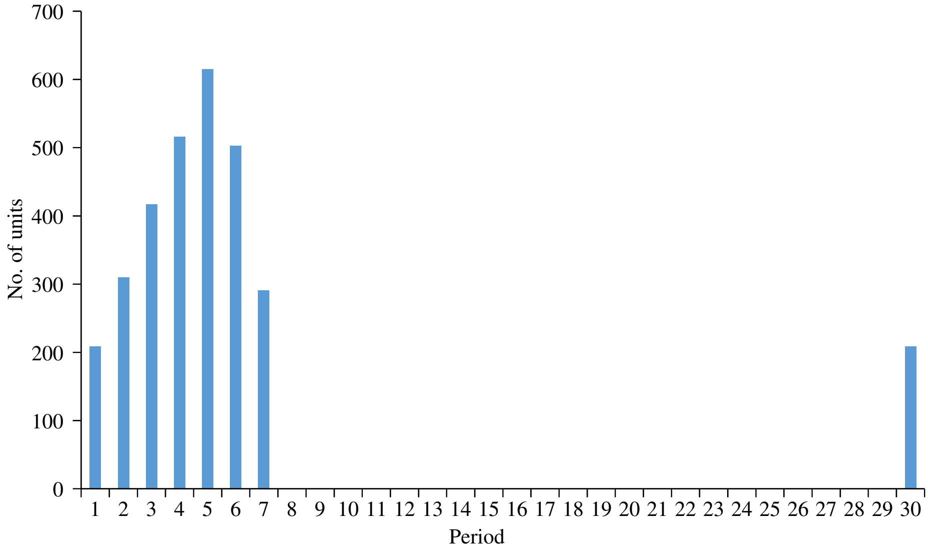
2.3.3. Results. At this point, we can observe the results. After completing the first run of this scenario, it is obvious ordering based on net inventory position is preferable to that of ordering based on net inventory. Retailer B's profit is positive, whereas Retailer A's profit is negative. As both Retailer A and Retailer B have the same external demand with the same costs, we conclude Retailer A manages inventory less efficiently than Retailer B.

Retailer A. The analysis here is similar to the analysis of Retailer A in Exercise 1. It takes five periods until Retailer A receives its first order. During these five periods, Retailer A orders grow because of an increasing number of backorders. From periods 5 through 8, the backorder numbers decrease; however, Retailer A continues to order. From periods 9 through 29, Retailer A has enough inventory on hand to supply its demand. Finally, the situation in period 30 is about the same as at the beginning of the simulation. As in Exercise 1 we observe a wave of orders (and backorders) followed by a wave of inventory. See Figures 9–12.

Retailer B. The behavior of Retailer B is different here than in Exercise 1. Because of the fixed ordering cost, Retailer B does not order every period. At the beginning of the simulation, Retailer B orders $S_B = 760$ units as its inventory position is initially 0, which is less than $s_B = 515$. Only after three periods is its inventory position less than s_B. At this time it replenishes exactly the demand in the last three periods and in this way brings its inventory position back to S_B. In most cases (demand is stochastic), Retailer B orders every three periods, and whenever it orders, it orders the total demand since its last order. Moreover, in most cases, there are no backorders. See Figures 13–15.

2.3.4. Comparison Between Retailer A and Retailer B. Comparing the results for Retailer A and Retailer B, we see some similarities and some differences. Retailer A's ordering/inventory/backorder profile is periodic with a periodicity of 29 periods. It has a wave of backorders followed by a wave of inventory. Retailer B's profile is also periodic, but with a

Figure 9. Orders at Retailer A.



periodicity of three periods after the initial run-in time of five periods. Retailer B rarely has backorders.

To compare the costs, let us examine a typical period for each retailer. To do this, run the simulator to period 5 and record the total values for Retailer A and Retailer B (separately) of replenishment cost, holding cost, and shortage cost. Now run the simulator to period 93 and again record the total value for Retailer A and Retailer B (separately) of replenishment cost, holding cost, and shortage cost. The value of each total cost (replenishment, holding, and shortage) from period 6 to period 93 is equal to the difference between the total value at period 93 and the total value at period 5.

We can see from Table 1 that Retailer B has a smaller holding cost and a smaller shortage cost than Retailer A from periods 6 to 93. However, Retailer B has a greater replenishment cost.

Figure 10. Backorders at Retailer A.

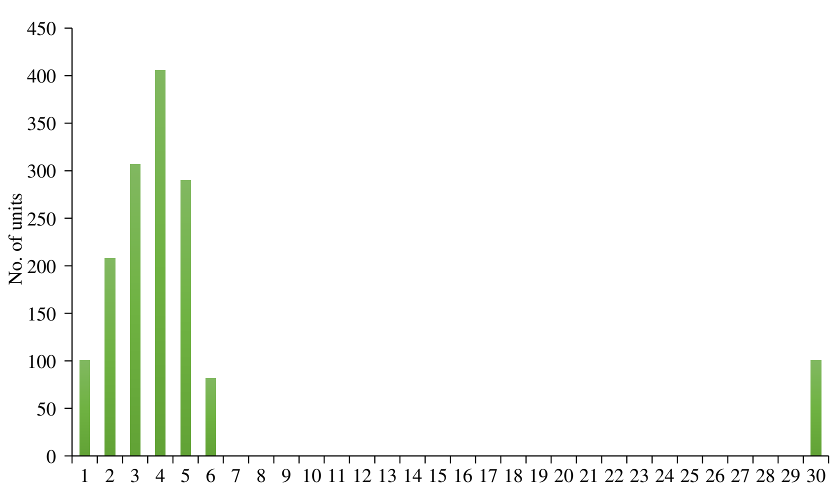


Figure 11. On-hand inventory at Retailer A.

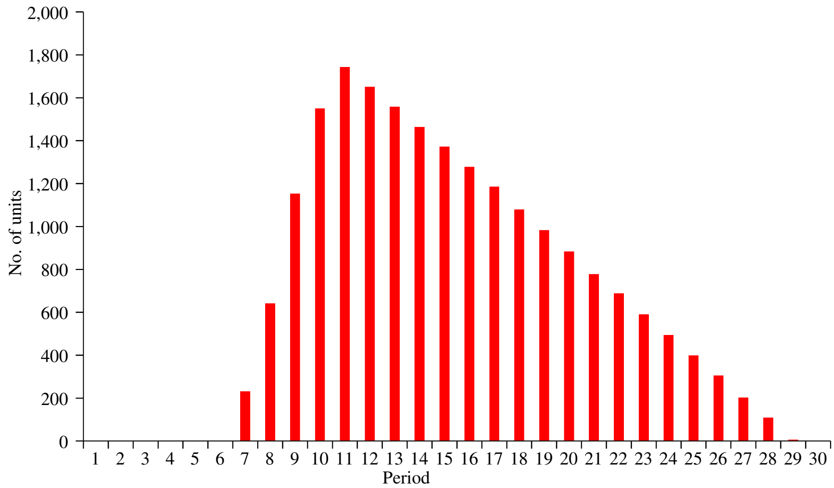


Figure 12. Periodicity of orders and inventory at Retailer A.

Figure 13. Orders at Retailer B.

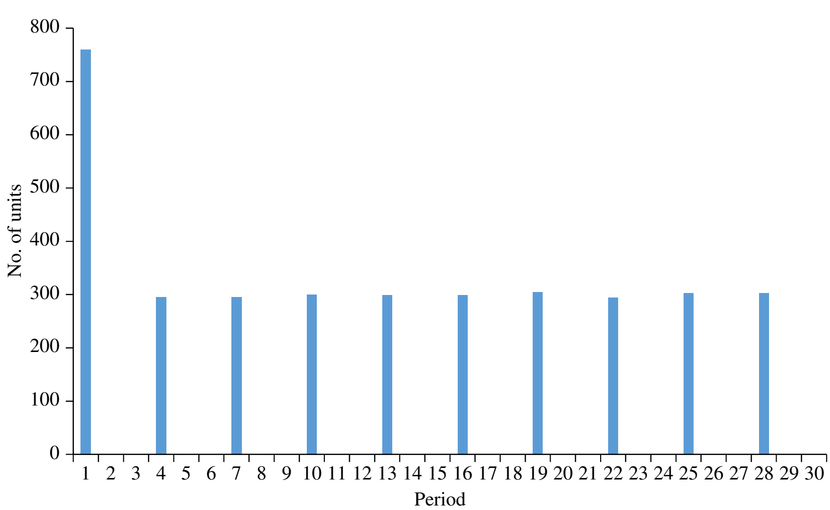


Figure 14. Backorders at Retailer B.

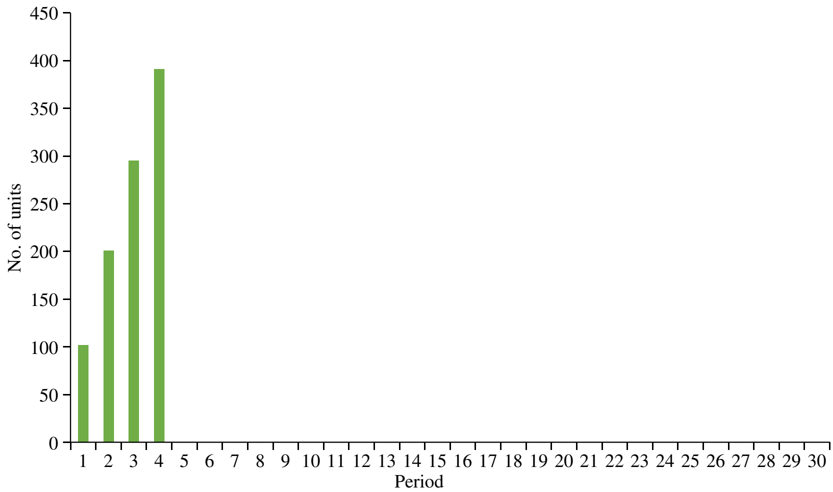
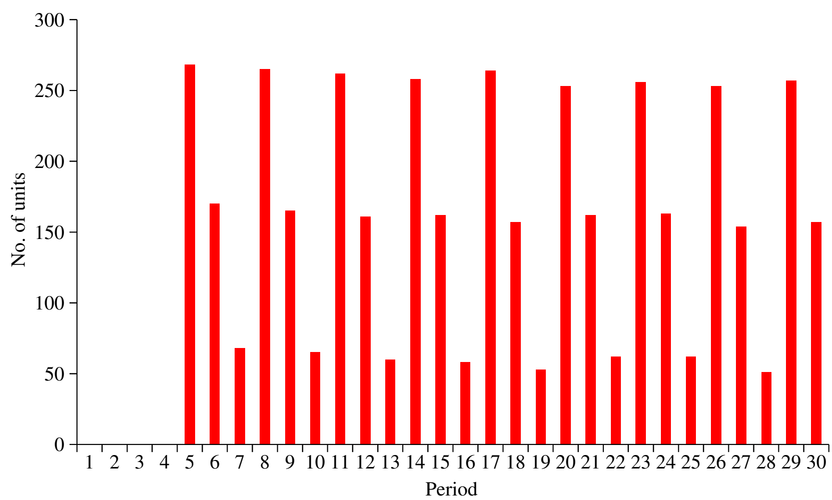


Figure 15. Inventory on hand at Retailer B.



2.4. List of Additional Exercises

Exercise 1 and Exercise 2 are two of many possible exercises. Many more exercises are currently being developed, and many more are possible. For example, there are the following:

- Echelon inventory position versus net inventory position. This exercise will consider a three-stage supply chain. A manufacturer supplies a warehouse that supplies a retailer. There will be a lead time both between the manufacturer and the warehouse and between the warehouse and the retailer. Exercises 1 and 2 showed that the retailer should consider

Table 1. Cost analysis.

	Replenishment cost		Holding cost		Shortage cost	
At the end of	Retailer A	Retailer B	Retailer A	Retailer B	Retailer A	Retailer B
Period 5	1,500	600	0	268	7,896	5,934
Period 93	9,000	9,300	59,159	14,210	30,546	5,934

inventory position when ordering. This idea can immediately be transferred to the warehouse and means that when ordering, the warehouse should consider units that it has ordered and that have yet to be delivered. This exercise will show that the warehouse should also consider the inventory that is at (or on its way to) the retailer when it is making an ordering decision. That is, the warehouse should use net echelon inventory position.

- Echelon inventory with multiple retailers. This exercise repeats the previous exercise, but this time with multiple retailers. It shows that the advantages of using net echelon inventory position over using net inventory position are even more pronounced.
- Many companies use forward local warehouses to pool inventory when supplying multiple local retailers. This exercise will compare a system with a faraway manufacturer supplying multiple retailers and a system where the faraway manufacturer supplies a local warehouse that supplies the multiple retailers. It will be demonstrated that even when the local warehouse increases the total lead time, the pooling advantages of the local warehouse can outweigh the increased lead time disadvantages.

2.5. Section Summary

Previous SCS users have repeatedly reported satisfaction with the simulator and indicated that the SCS's scenarios were relevant for their future work as engineers. Most of them believe that they will apply the skills they acquired during their experience with the SCS in their future work. Participants also mentioned that even without a deep theoretical background, they obtained skills that will be valuable for them during their current studies as well as later on in their professional career. This is because the SCS develops students' analytical abilities in conjunction with tangible experience regarding practical potential challenges.

3. The Project Team Builder (PTB)

The Project Team Builder was developed at the Technion for internal use as a supplement to traditional lectures and books in the area of project management. Early versions of PTB were used by universities in Europe, North America, Australia, and Asia. Feedback from PTB users has been encouraging, and PTB has been recognized with an award from the Project Management Institute.

Recently, a new version of PTB was developed with a new easy-to-use user interface. This new version is a flexible project management training simulator. Flexibility is designed into the PTB via a library of different project scenarios that enable the user to develop her own scenarios or case studies. Real or imaginary projects are the basis for scenarios that focus on one or more of the following project management knowledge areas:

1. Project scope management—determining the work that needs to be done to achieve the project goals and developing a plan that satisfies those goals by selecting the right operational alternatives.
2. Product scope management—determining the features and functions or quality of the project deliverables and developing a plan that satisfies those goals by selecting the right combination of technological alternatives.
3. Time management—determining the sequencing of project activities and the start time of each activity.
4. Cost management—developing a plan that minimizes the total cost of performing the project while achieving the project goals. The costs included in the PTB are the cost of resources used to perform project activities as well as the cost of idle resources, the cost of assigning additional resources to the project and the cost of releasing such resources, the cost of splitting activities and the cost of materials and other fixed costs, and finally a penalty cost for late completion or a bonus for early delivery.
5. Risk management—determining the sources of risks, mitigating those risks, and monitoring the project throughout its execution to correct any deviations from project plans.

6. Resources management—determining the resources that are needed for the project, the time when these resources are needed, and their quantities.

7. Trade-off analysis—developing a plan that simultaneously takes into consideration the above knowledge areas by developing a Pareto-efficient project plan.

The Project Team Builder is designed to support teaching of project management in two ways:

1. For the basic courses in operations management, a library of project case studies or scenarios is available. These scenarios are classified according to their level of difficulty (based on the presence and degree of uncertainty, limitations on the availability of resources and cash that impose tight and sometimes conflicting constraints). Easy scenarios are deterministic with practically unlimited resources and budget. Difficulty is introduced by uncertain duration of activities, breakdown of machines, and no-show of workers as well as tight resource and cash constraints.

2. For advanced courses (typically dedicated project management courses) a scenario builder is used and the students are asked to analyze a real project and to develop a proper scenario that they plan, monitor, and control on the Project Team Builder.

The goal of the simulation is to develop a project plan that minimizes the project cost while ending the project on or before a given due date and satisfying all the requirements. The plan is executed by the user who can monitor and control the project during execution and take corrective actions when necessary. Corrective actions are necessary when, because of uncertainty, the simulated progress of the project deviates from the plan, causing the project to be late or over budget.

Uncertainty is present in the estimated duration of project activities—a three-point estimate is used with optimistic, most likely, and pessimistic duration estimates for each activity. Using a triangular distribution, the actual duration of each activity is randomly generated during the simulation run.

Availability of resources is also a source of uncertainty as machines break down and workers do not show up in some periods during project execution. The probability of no-show and machine breakdowns is binomial, and in each period the availability of each resource unit is randomly generated.

Using the PTB, users can practice the tools and techniques of project management in a safe environment, moving gradually from simple deterministic projects to complex, highly constrained stochastic simulations.

The PTB is used as an add-on to courses in operations management as an assignment that integrates the tools and techniques such as a Gantt chart, critical path, and resource management. This assignment comes with a built-in video tutorial so the teacher does not have to spend time in class explaining the PTB and its use. The students learn how to use the simulator and perform the simulation on their own. The automatic report generator produces a detailed report at the end of the run that is turned in for grading.

The PTB can also be used for a full course on project management—each subject discussed in class is practiced on a scenario focusing on the subject matter, and at the end of the course, students develop their own scenario based on a real or imaginary project. By analyzing a project from start to finish, throughout the whole life cycle, students learn how to see the big picture and to integrate the bits and pieces of project management knowledge areas.

In the following tutorial the basic modules of the Project Team Builder are discussed. It will help you get started. All the information provided here is given in more detail in the PTB User Manual and on the website of Sandboxmodel: http://www.sandboxmodel.com/content/simulation-based-training.

3.1. Project Team Builder Principles

The Project Team Builder is a simulation-based training environment for project management. PTB provides a dynamic, stochastic environment for training and is based on the following principles:

(a) *A simulation approach.* The PTB simulates one or more projects. The simulation is controlled by a simple user interface and no knowledge of simulation or simulation languages is required.

(b) *A case study approach.* The PTB is based on a simulation of case studies called scenarios. Each case study is a project or a collection of projects performed in a dynamic stochastic environment. In some scenarios the projects are performed under schedule, budget, and resource constraints. The details of these case studies are built into the simulation and all the data required for analysis and decision making are easily accessed via the user interface.

(c) *A dynamic approach.* The case studies built into the PTB are dynamic in the sense that the situation changes over time. A random effect is introduced to simulate the uncertainty in the environment, and decisions made by the user cause changes in the state of the system simulated.

(d) *A model-based approach.* A decision support system is built into the PTB. This system is based on project management concepts. The model base contains well-known models for scheduling, budgeting, resource management, and monitoring and control. These models can be consulted at any time.

(e) *Further support for decision making.* A database is built into the PTB. Data on the current state of the simulated system are readily available to the users; it is possible to use the data as input to the models in the model base to support decision making. Furthermore, by using special history mechanisms, the user can access data on his past decisions and their consequences.

(f) *User friendliness and GUI.* The PTB is designed as a teaching and training tool. As such, its graphic user interface is friendly and easy to learn. Although quite complicated scenarios can be simulated, and the decision support tools are sophisticated, a typical user can learn how to use the PTB within an hour.

(g) *An integrated approach.* Several projects can be managed simultaneously on the PTB. These projects can share the same resources and a common cash flow.

(h) *Integration of processes.* This includes planning processes, executing processes, and monitoring and controlling processes. All these processes are performed simultaneously in a dynamic stochastic environment.

(i) *Integration with commercial project management tools.* The PTB is integrated with Microsoft Project so that the users can export the data to Microsoft Project in order to analyze the scenario and to support its decisions with tools that are commercially available.

3.2. Project Team Builder Scope

With PTB, students can learn how to deal with project planning and control using a variety of models such as the critical path method, Gantt charts, resource allocation and leveling, cash flow management, and performance optimization. The following formulations define the families of problems that PTB can simulate:

3.2.1. Assumptions and Notations. The following notation is used to describe the proposed model.

Index and Sets

- j: index for project activities; $j = 0, 1, 2, \ldots, J, J+1$, where J represents the number of activities in the project. The fictitious or dummy activities 0 and $J+1$ correspond to the beginning and the end of the project, respectively.
- m: mode index of an activity j; each mode defines the number of required resources, duration, and performance measures of a particular activity, $m_j = 1, 2, \ldots, M_j$, where M_j is the number of modes associated with activity j.
- k: index for (renewable) resource types, $k = 1, 2, \ldots, K$, where K represents the number of (renewable) resource types available during the project.

- v: index for a project system characteristic, $v = 1, 2, \ldots, V$, where V determines the number of system characteristics.
- $P(j)$: set of immediate predecessors of activity j.

Time Parameters

- T: the project's due date.
- d_{mj}: duration of activity j if performed in mode m_j. Each duration is assumed to be a nonnegative integer.
- $T_{\max}$: upper bound on the project completion time computed as $T_{\max} = \sum_{j=1}^{J} \max_{m_j=1,\ldots,M_j} d_{m_j}$.
- FT_k: lead time for firing a resource k.
- HT_k: lead time for hiring a resource k.

Resource Parameters. Resource parameters are assumed to be nonnegative real numbers.

- A_{kt}: number of resource k units available in period t.
- R_{mjk}: per-period amount of resource k required to perform activity j under the mode m_j.
- $A_{k\min}$: minimum units of resource k allowed per period.
- $A_{k\max}$: maximum units of resource k allowed per period.

Budget Parameters

- FC_{mj}: fixed cost of activity j if performed in mode m_j.
- W_k: per-period cost per unit of utilized resource k.
- WI_k: per-period idle cost per unit of resource k (i.e., cost when a resource k is unutilized).
- F_k: firing cost of resource k.
- H_k: hiring cost of resource k.
- P: penalty per period for finishing the project after due date T, $P \geq 0$.
- B: bonus per period for finishing the project before due date T, $B \geq 0$.
- I_j: positive income from task j earned after the completion of activity j.
- α_t: present value discount factor for t periods.
- C_0: positive cash available at the start of the project.
- C_t: net cash position at period t.
- $C_{\min}$: minimum required net profit.

Performance Parameters

- Q_{vmj}: value of system requirement v for activity j if performed in mode m.
- $F_v(Q_{v1}, \ldots, Q_{vJ})$: function that maps the value of system characteristic v for the entire project.
- $F_{v\min}$: minimum required value of F_v.
- $F_{v\max}$: maximum required value of F_v.
- $P(F_v(Q_{v1}, \ldots, Q_{vJ}))$: technological performance function for a project, assumed to be a real-valued function. In the literature, many approaches exist in order to evaluate it.

3.2.2. Problem Formulation I. In this first formulation, the decision variables determine the scheduling and mode execution for each activity:

- $$x_{m_j t} = \begin{cases} 1 & \text{if activity } j \text{ in mode } m_j \text{ is completed in period } t, \\ 0 & \text{otherwise.} \end{cases}$$

We propose to maximize project performance under resources, precedence, and budget constraints. Note that in our study, we consider both renewable and nonrenewable resources constraints, where cash is the only nonrenewable resource:

$$\text{Maximize} \ \left\{ P(F_v(Q_{v1}, \ldots, Q_{vJ})) \ \forall\, v = 1, \ldots, V \right\} \tag{1a}$$

subject to

$$\sum_{m_j=1}^{M_j}\sum_{t=1}^{T_{\max}} x_{m_j t} \quad \forall\, j=1,\dots,J, \tag{1b}$$

$$\sum_{m_j=1}^{M_j}\sum_{t=1}^{T_{\max}} x_{m_j t}(t-d_{m_j}) \geq \sum_{m_i=1}^{M_i}\sum_{t=1}^{T_{\max}} x_{m_i t}\cdot t \quad \forall\, j=1,\dots,J,\ \forall\, i\in\mathcal{P}(j), \tag{1c}$$

$$\sum_{j=1}^{J}\sum_{m_j=1}^{M_j}\sum_{q=t}^{t+d_{m_j}-1} x_{m_j q}\cdot R_{m_j k} \leq A_{kt} \quad \forall\, k=1,\dots,K \quad \forall\, t=1,\dots,T_{\max}, \tag{1d}$$

$$A_{kt} = A_{k0} \quad \forall\, t=1,\dots,T_{\max}, \tag{1e}$$

$$\begin{aligned} C_t - C_{t-1} = {} & B_t + \sum_{j=1}^{J}\sum_{m_j=1}^{M_j} x_{m_j t}\cdot I_j - \sum_{j=1}^{J}\sum_{m_j=1}^{M_j} x_{m_j t}\cdot FC_{jm} \\ & - \sum_{j=1}^{J}\sum_{m_j=1}^{M_j}\sum_{q=t}^{t+d_{m_j}-1} x_{m_j q}\sum_{k=1}^{K} W_k\cdot R_{m_j k} \\ & - \sum_{k=1}^{K}\left(A_{kt}\cdot\sum_{s=1}^{t}\sum_{m=1}^{M_j}(1-x_{m_j s}) - \sum_{j=1}^{J}\sum_{m_j=1}^{M_j}\sum_{q=t}^{t+d_{m_j}-1} x_{m_j q}\cdot R_{m_j k}\right)\cdot WI_k \\ & \forall\, t=T+1,\dots,T_{\max}, \end{aligned} \tag{1f}$$

$$C_t \geq 0 \quad \forall\, t=1,\dots,T_{\max}, \tag{1g}$$

$$B_t = B \quad \text{if} \sum_{j=1}^{J}\sum_{m_j=1}^{M_j}\sum_{s=1}^{t} x_{m_j s} = J \quad \forall\, t=1,\dots,T, \tag{1h}$$

$$P_t = P, \quad \text{if} \sum_{j=1}^{J}\sum_{m=1}^{M_j}\sum_{s=1}^{t} x_{jms} < J \quad \forall\, t=T+1,\dots,T_{\max}, \tag{1i}$$

$$\sum_{t=1}^{T_{\max}} \alpha_t(C_t - C_{t-1}) \geq C_{\min} \tag{1j}$$

$$Q_{vj} = \sum_{m_j=1}^{M_j}\sum_{t=1}^{T_{\max}} x_{m_j t}\cdot Q_{v m_j}, \quad \forall\, v=1,\dots,V,\ \forall\, j=1,\dots,J. \tag{1k}$$

The objective in (1a) is to maximize the project's performance.

The mathematical program includes binary decision variables $x_{m_j t}$. Constraint (1b) ensures that each activity is performed in only one of the possible modes and no later than the maximum completion time of the project. We assume that we cannot switch modes if the activity has already started. The first constraint also guarantees that there is a feasible schedule without preemption. Constraint (1c) maintains the precedence relations among activities. The resource constraints are satisfied by imposing constraint (1d). In this first problem formulation, the availability per period of each renewable resource is fixed (1e). The evolution of the cash position is described via constraint (1f). Constraint (1g) prevents bankruptcy during the project. Bonus and penalty are defined in constraints (1h) and (1i). Constraint (1j) ensures that the required minimum profit is achieved. The last constraint, constraint (1k), denotes the performance measure of each activity as a function of its chosen mode.

3.2.3. Problem Formulation II. In the second formulation, we allow a different resource profile than in the first formulation, where the number of available resource units was constant and equal to their initial number (A_{k0}). We add flexible capacity, i.e., the possibility of increasing or decreasing capacity at the beginning of each period. Since these resources are renewable, in practice, this means that a project manager can hire or fire resources during the project. Obviously, such decisions may require cash and time (for example, when a manager decides to fire an employee, it does not take effect immediately and requires some compensation). Consequently, in this new problem, we add decision variables to deal with resource hiring and firing decisions:

- FN_{kt}: number of fired resources k in period t.
- HN_{kt}: number of hired resources k in period t.

Again, the objective function (1a) is to maximize project performance subject to several constraints.

The new problem is very similar to the first formulation described above. The changes only pertain to constraints (1e) and (1f). In the new formulation, constraint (1e) describes the available resources' evolution during the project as a function of hiring and firing decisions in each period, so the resource capacity is flexible:

$$A_{kt} = A_{k(t-1)} + HN_{k(t-TH_k)} - FN_{k(t-TN_k)} \quad \forall k = 1, \ldots, K, \forall t = 1, \ldots, T_{\max}.$$

In addition, the hiring and firing costs are integrated into the cash position constraint (1f), which changes to

$$\begin{aligned} C_t - C_{t-1} = {} & B_t + \sum_{j=1}^{J}\sum_{m_j=1}^{M_j} x_{m_j t}\cdot I_j - \sum_{j=1}^{J}\sum_{m_j=1}^{M_j} x_{m_j t}\cdot FC_{jm} - \sum_{j=1}^{J}\sum_{m_j=1}^{M_j}\sum_{q=t}^{t+d_{m_j}-1} x_{m_j q} \\ & \cdot \sum_{k=1}^{K} W_k \cdot R_{m_j k} - \sum_{k=1}^{K}\left(A_{kt}\cdot \sum_{s=1}^{t}\sum_{m=1}^{M_J}(1 - x_{m_j s}) - \sum_{j=1}^{J}\sum_{m_j=1}^{M_j}\sum_{q=t}^{t+d_{m_j}-1} x_{m_j q}\cdot R_{m_j k}\right) \\ & \cdot WI_k - \sum_{k=1}^{K}(FN_{kt}\cdot F_k + HN_{kt}\cdot H_k) - P_t \quad \forall t = 1, \ldots, T_{\max}. \end{aligned}$$

3.2.4. Example of How PTB Can Be Used for Instruction: Development of a Radar System. In this scenario your task is to manage a new radar system development project. Information on radar systems taken from *Wikipedia* will be given. The project scope consists of five tasks in one work package. The tasks and the precedence relations among them are listed in Figure 16. The project network and data are presented in Figure 17.

The project should finish in 15 periods, and there is a penalty for late completion and a bonus for early completion. Two types of resources are used in the project: engineers and technicians. Resource information is presented in Figure 18.

The product scope includes a transmitter, a receiver, and an antenna. The performance metrics are defined by the requirements found in Figure 19.

The range is determined by the radar equation (details of this and other equations will be provided):

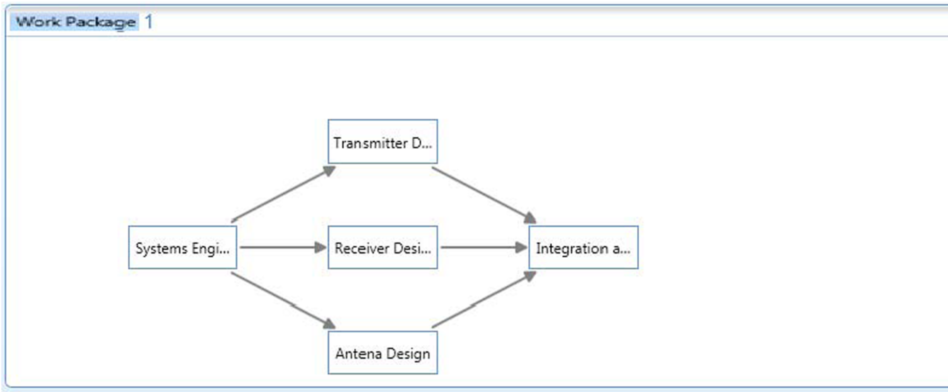
$$\text{Range} = \text{POWER}\big([\text{TP}] * [\text{RS}] * [\text{AG}], 0.25\big),$$

FIGURE 16. Tasks and precedence relationships.

Task Info

Work package name	Task name	Predecessors
Work package 1	Systems engineering	
Work package 1	Transmitter design	Systems engineering
Work package 1	Receiver design	Systems engineering
Work package 1	Antenna design	Systems engineering
Work package 1	Integration and testing	Transmitter design, receiver design, antenna design

FIGURE 17. Project network and data.



Scenario Information

Work Package Name	Number of Tasks	Target Date	Initial Cash	Bonus per Period	Penalty per Period	System Engineering Enabled
Work Package 1	5	15	100000	10000	20000	True

FIGURE 18. Resource information.

Resource Management

Name	Available Units	Units Available in Lead Time	Cost/Period	Idle Cost/Period	Firing Cost	Hiring Cost	Show Up Probability (%)	Firing Lead Time	Hiring Lead Time	Minimum Units	Maximum Units
Engineers	10	10	100	50	50	50	80	1	1	1	30
Technicians	10	10	50	10	40	20	85	1	1	2	50

FIGURE 19. Performance requirements.

System Requirements

Name	Formula	Importance	Minimum Value	Desired Value	Maximum Value	Best Mode	Evaluation
Range	POWER([TP]*[RS]*[AG],0.25)	7	10	12	40	Maximum	NA
Quality	[SEQ]*[QT]*[QR]*[QA]*[QI]*100	8	0	75	100	Maximum	NA
Reliability	[AR]*[IR]*[TR]*[RR]*100	6	0	65	100	Maximum	NA

where TP is the transmitter power, RS is the receiver sensitivity, and AG is the antenna gain. The quality is determined by the following equation:

$$\text{Quality} = [\text{SEQ}] * [\text{QT}] * [\text{QR}] * [\text{QA}] * [\text{QI}] * 100,$$

where SEQ is quality of the systems engineering effort, QT is quality of the transmitter, QR is quality of the receiver, QA is quality of the antenna, and QI is quality of the integration effort. The reliability is determined by the following equation:

$$\text{Reliability} = [\text{AR}] * [\text{IR}] * [\text{TR}] * [\text{RR}] * 100,$$

where AR is reliability of the antenna, IR is reliability of the integration effort, TR is reliability of the transmitter, and RR is reliability of the receiver.

Your task is to plan and execute the project—to complete the project scope on time and at minimum cost while meeting or exceeding the required performances of the radar system. To perform this task you can hire and fire resources using the initial cash of $ 100,000 allocated to the project.

3.3. Educational Goals

The PTB exercises are designed to teach the following concepts and principles:

1. Scheduling
   - The Gantt chart
   - The critical path method
   - The PERT method
   - Scheduling risk management
2. Resource management
   - Renewable and depleting resources
   - Resource leveling
   - Resource allocation
3. Cost management
   - Fixed costs and variable costs
   - Bonuses and penalties
   - Management reserve
   - Cost of risk mitigation
   - Cash flow management
4. Risk management
   - Risk identification
   - Risk analysis
   - Risk mitigation
   - Risk monitoring and control
5. Integration management
   - Project planning and the Pareto-efficient frontier of project plans
   - Trade-off analysis
   - Integration of time cost resources and risk issues
   - Monitoring and control during project execution
6. Requirements management
   - Stakeholders' analysis
   - Quality function deployment
   - Value analysis and benefit calculations
7. Lean project management
   - Maximizing value and minimizing waste
   - Feasibility analysis and constraints
   - Requirements analysis and gold plating

The teacher can decide on which concepts and tools to teach and develop her own project scenarios accordingly, or she can use the library of project scenarios that comes with the Project Team Builder. These concepts are taught along with the lectures on the theoretical aspects. At the end of the course, the students can learn how to develop their own project scenarios by researching a real project and collecting the data required for the scenario. This is a good way to integrate all the material learned as the students are exposed to a real project, the difficulty to collect real data, and the complexity of integrating all of the above concept tools and techniques in a real-life-like situation.

4. Effectiveness of Teaching with the Simulators

Confucius said, "I hear and I forget. I see and I remember. I do and I understand." This is the essence of SBT. We have to experience things ourselves in order to really understand them. A well-designed simulator supports a process of action-based learning. Instead of talking about different ways of doing things, simulators offer an opportunity to try different ways of doing things without risking the consequences of doing so in the real world. As a result, games and simulations have become widely recognized methods for instruction and learning and are becoming increasingly more important.

The effectiveness of SBT depends on instructors rationale for using simulations as learning tools (Magana et al. [18]). Still, using SBT for education offers several advantages over traditional techniques, such as supplying hands-on practice and allowing for the development of skills at a faster pace (Salas et al. [24]).

Several experiments have investigated the hypothesis that using simulation-based training has the potential to improve not only the learning process but its outcome as well. For example, Parush et al. [21] tested the impact of simulation-based training on the learning curve of users both for the case of repeating the same scenario and for the case of training on different scenarios. They found that performance and knowledge transfer in the area of project management were significantly better when the simulator was used. Davidovitch et al. [6] tested the impact of simulation-based training on the learning-forgetting-relearning process and the impact of a learning history mechanism built into the simulator on the process. Davidovitch et al. [7] tested the hypothesis that the learning process improves with the functional fidelity in simulation-based training of project management. The improvement in the learning-forgetting-relearning process and the impact of the functional fidelity were both significant.

Nembhard et al. [20] compared competitive and cooperative strategies for learning project management using simulators in teams and found that the best approach is to mix the two strategies. Parush et al. [22] investigated the impact of simulation-based training on team training, simulating resource allocation in a matrix structure organization. Cohen et al. [4] tested the effectiveness of simulation-based training for the training of systems engineers. These *experiments* show that simulation-based training supports team learning and the training of experienced engineers.

Zwikael et al. [28] studied the impact of scenario flexibility (the ability to fit the simulated scenario to the trainees and to the course objectives) and found that one size does not fit all, and it is important to match the scenario difficulty to the level of knowledge of the students.

Based on these studies it is clear that simulation-based training has great potential to improve the way we teach and train, and simulators such the Project Team Builder and the Supply Chain Simulator are just a part of the beginning of a new era of simulation-based training.

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