

# **SIMULATION AS A TOOL FOR PRODUCTION SYSTEM DESIGN IN CONSTRUCTION**

**Thais da C. L. Alves<sup>1</sup>, Iris D. Tommelein<sup>2</sup> and Glenn Ballard<sup>3</sup>**

## **ABSTRACT**

In this paper, the authors discuss the concepts of variability, buffers, and batches, as well as the interactions between them. The discussion aims at contributing to the identification of factors that impact production systems design, which includes the definition of buffer locations, buffer profiles, batch sizes, etc. The authors use a simulation model developed using STROBOSCOPE to represent five different scenarios for planning, fabrication, shipping, and installation of sheet metal ductwork in order to illustrate how production system design choices may affect the lead time needed to deliver a project. The data used to develop the model was obtained from time studies performed by the authors as well as from interviews conducted with field superintendents. In order to develop the model, the authors needed basic information about activities pertaining to the delivery of sheet metal ductwork. Modeled durations and quantities are approximations based on the data collected. The model highlights the need for and importance of reliable data when designing production systems and simulation models thereof. Effort needs to be put in by the construction industry and researchers to gather more representative sets of data that can be used to design production systems.

## **KEY WORDS**

Simulation, production system design, buffers, batches.

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<sup>1</sup> Visiting Scholar, Structural Engineering and Construction Department, Federal University of Ceará, Campus do Pici, s/n, Bloco 710, Pici, CEP: 60455-760, Fortaleza, CE, Brazil, Phone: +55 85 3366-9607, Ext. 36, thaiscla@yahoo.com

<sup>2</sup> Professor and Vice Chair of Instruction, Civil and Env. Engineering. Department, 215-A McLaughlin Hall, Univ. of California, Berkeley, CA 94720-1712, Phone +1 510/643-8678, FAX 510/643-8919, tommelein@ce.berkeley.edu

<sup>3</sup> Associate Adjunct Professor, Civil and Envir. Engrg. Department, 215 McLaughlin Hall, University of California, Berkeley, CA 94720-1712, FAX 510/643-8919, ballard@ce.berkeley.edu

## INTRODUCTION

In this paper, the authors discuss the concepts of variability, buffers, and batches, as well as the interactions between them. The discussion aims at contributing to the identification of factors that impact production systems design, which includes the definition of buffers profiles (type, location, and size), batch sizes, etc.

This paper advocates that the understanding of the characteristics of a specific industry and the supply chain in which a company in that industry operates are necessary for designing production systems. Central to this discussion is understanding the occurrence and causes of variability in production systems, as well as potential uses of buffers to mitigate the effects of variability in these systems. One objective of production system design is to create a system that is capable of meeting demand. Demand is typically uncertain and must be forecast. Since demand can be uncertain, production systems have to be buffered in order to be able to absorb variations while still meeting demand. The quest to match production system capabilities with demand has its costs, which can be high or low depending on the buffer profiles and batch sizes defined for the production system. Therefore, the study of buffers and batches is fundamental to design of production systems.

## VARIABILITY

Variability is defined as “the quality of nonuniformity of a class of entities” (Hopp and Spearman 2000, p. 249). In manufacturing, for example, the time to complete an operation in a machine may always be the same—in which case there is no variability—or may vary largely each time the operation is performed—in which case there is high variability. The concept of variability is related to the concept of randomness, which is the occurrence of variations that *appear* to be out of one’s control. A series of outputs may look (*appear*) random to us because we may not have enough information to describe the behavior of the system, and its components, generating the outputs.

Variability can be controllable, e.g., if it is introduced in systems as a result of managerial decisions, or random, e.g., if it cannot be controlled or predicted (Hopp and Spearman 2000). Some of the root causes of variability in the construction industry are the lack of standardization of parts and operations; the managerial indicators, penalties, and incentives used (Kim 2002); the degree of linkage between construction activities (Howell et al. 1993); and low levels of activities completed as planned (Ballard 2000). Root causes of variability in the construction industry and specifically in the sheet metal ductwork supply chain are discussed in more detail throughout this paper.

## DEMAND VARIABILITY AND FORECASTING

The design of production systems involves the match of load (i.e., demand) and capacity. The work load for a system is defined based on an estimate of the future demand, which is subject to variability; this estimate represents the forecast. Managers should aim at developing forecasts that support the planning process and result in robust plans that work well in most of the situations (Hopp and Spearman 2000).

Forecasts can be developed through the use of quantitative and qualitative methods (e.g., Schmenner 1993). Quantitative methods include for instance the use of time series, and the computation of values for different periods using moving averages or exponential smoothing techniques. Qualitative techniques include the Delphi method, which uses

experts' opinions elucidated in a panel session. The experts' opinions are subsequently summarized and discussed in the panel for several rounds of synthesis and discussion of opinions until consensus is reached. The choice of the adequate forecasting method depends on the level of precision one wants to achieve, the cost to develop the forecast, as well as the consequences that may result from the appropriateness of the forecast technique being used.

## **BUFFERING AND BATCHING**

The definition of buffering and batching practices are an important part of production systems design. Moreover, batching practices—whether intentional or not—affect the way buffers accumulate in a system (Alves and Tommelein 2004) and overall system performance. This section discusses concepts, implementations, and implications of some buffering and batching practices.

### **BUFFERING**

Buffers are understood in this paper as “resource cushions, i.e., money, time, materials, space, etc., used to protect processes against variation and resource starvation” (Alves and Tommelein 2004, p. 2). Buffers can be used to protect a system against variability through the use of inventory, capacity, time, or a combination of the previous (Hopp and Spearman 2000). The use of buffers protects the system against material shortages, poor customer service, long lead times, operations cycle times' randomness amongst other problems caused by variability.

Shingo (1989) suggest a ‘cushion stock system’ to deal with the introduction and sizing of buffers in production systems. He says that even though the Toyota Production System aims at achieving non-stock production, stocks are necessary to deal with unexpected events that may halt production. Therefore, first, he proposes that ‘cushion stocks’ be defined and not changed; and second, that production should run without relying on these stocks, and parts should be supplied in small lots directly to the assembly lines. These are trials so that the production line can be evaluated and buffers sized accordingly. Shingo stresses that items should be ‘borrowed’ from these stocks only when there is a need for that (e.g., equipment breakdown) and they should be replenished the next day so that the ‘cushion stock’ maintains its initial level.

### **BATCHING**

Batching practices have a direct relationship with the way buffers are located and sized in a system. For instance, batch sizes may help a production system in achieving minimum quotas for buffers to avoid starvation in the system (Arbulu et al. 2002).

The Toyota Production System is an example of a system that challenged the idea of fixed setup- and long lead-time durations by working out ways to reduce them inside and outside Toyota's plants (Shingo 1988). One practice used by Toyota to reduce setups includes the Single-Minute Exchange of a Die (Shingo 1988), in which setups of machines and equipment are reduced to single-digit numbers. This innovation allowed Toyota to deal with small batches without compromising the efficiency of its production system while at the same time promoting flexibility and banishing the waste derived from the use of large batches.

## SIMULATION MODEL

The model we developed represents a project that requires the installation of 1,850 fittings. The data used to develop the model was obtained from time studies performed by the authors as well as from interviews conducted with field superintendents. The activity durations and fitting quantities are approximations based on the data collected and are expressed respectively in hours and units. With this model, the authors do not intend to deliver precise numbers on the installation of sheet metal ductwork on any specific project. Instead, they represent more generally how the modeled system works and provide insights on causes of variations and their effect on system performance. These insights may help managers plan buffers in their production systems.

The model was developed using STROBOSCOPE (Martinez 1996), a discrete-event simulation language specifically designed to model construction operations. STROBOSCOPE has been used by different authors to model construction activities (e.g., Tommelein 1998, Arbulu et al. 2002) but could be used for a number of applications in other domains as well. STROBOSCOPE “is a programming language that represents resources as objects that have assignable, persistent, and dynamic properties; and that can actively and dynamically take into consideration the state of the simulated process” (Martinez 1996, p. 406). According to Martinez (1996, p. 1) “(g)eneral purpose simulation systems (...) cannot easily model the multiple resource requirements and dynamic complexity of construction processes” whereas STROBOSCOPE can continuously access the state and properties of resources in the simulation model and take appropriate action. The symbols and commands shown in Figure 1 are specific to STROBOSCOPE and may be different from those used by other simulation languages. Rectangles represent activities. Circles represent queues which hold resources used to perform activities (activities’ names are shown in italics and queues’ names are underlined). The arrows represent the transfer of resources between queues and activities. This said, the simulation model presented in this paper is not constrained in any way by the use of STROBOSCOPE, that is, it could be replicated in other simulation languages.

## MODEL DESCRIPTION AND ASSUMPTIONS

In this model, all the fittings are considered equal. Therefore, sequencing and matching of ductwork were not modeled. The data the authors obtained from industry personnel are averages for planning, shipping, and installing generic types of ductwork expressed in linear feet per hour or pounds of sheet metal per hour. Therefore, the authors chose to simplify the model given that they did not have precise data on the activities modeled. A large set of data was not available to allow the authors to fit the data set into a specific probabilistic distribution. They assumed that the durations of activities are normally distributed. Sensitivity analysis was not carried out to evaluate the implications different probability distributions would have for the model. These are limitations of this model.

The model is triggered by the *Make\_Ready* activity, which processes the tasks from the Plan queue. The *Make\_Ready* activity screens scheduled tasks for constraints and pre-requisites before it releases them for fabrication and installation. In the model, when *Make\_Ready* ends, it GENERATEs a group of orders and areas queued respectively in the Order and Area\_Ready queues.

The *Fabricate* activity receives one order at a time from the Order queue and employs one worker (from the Shop\_Worker queue) to GENERATE a batch of 25 fittings. The batch of fittings is sent to the Fittings queue and waits to be shipped by the *Ship* activity.

The *Ship* activity uses 1 truck (from the Trucks queue) to transport 1 batch of fittings at a time to their destination, which is represented by the queue Site Fittings. Finally, the *Install* activity withdraws 1 batch of fittings from Site Fittings, 1 crew (2 Site Workers) from the Site Worker queue, and 1 area from the Area Ready queue. Then, it GENERATES a batch of installed ductwork represented by the Duct System queue.

The queues Shop Worker, Trucks, and Site Worker were initialized with resources that are related to the durations of each activity (i.e., activities need a certain number of resources to be completed at the times shown). They are part of the model's constraints and their definition is based on the data used to develop the model.

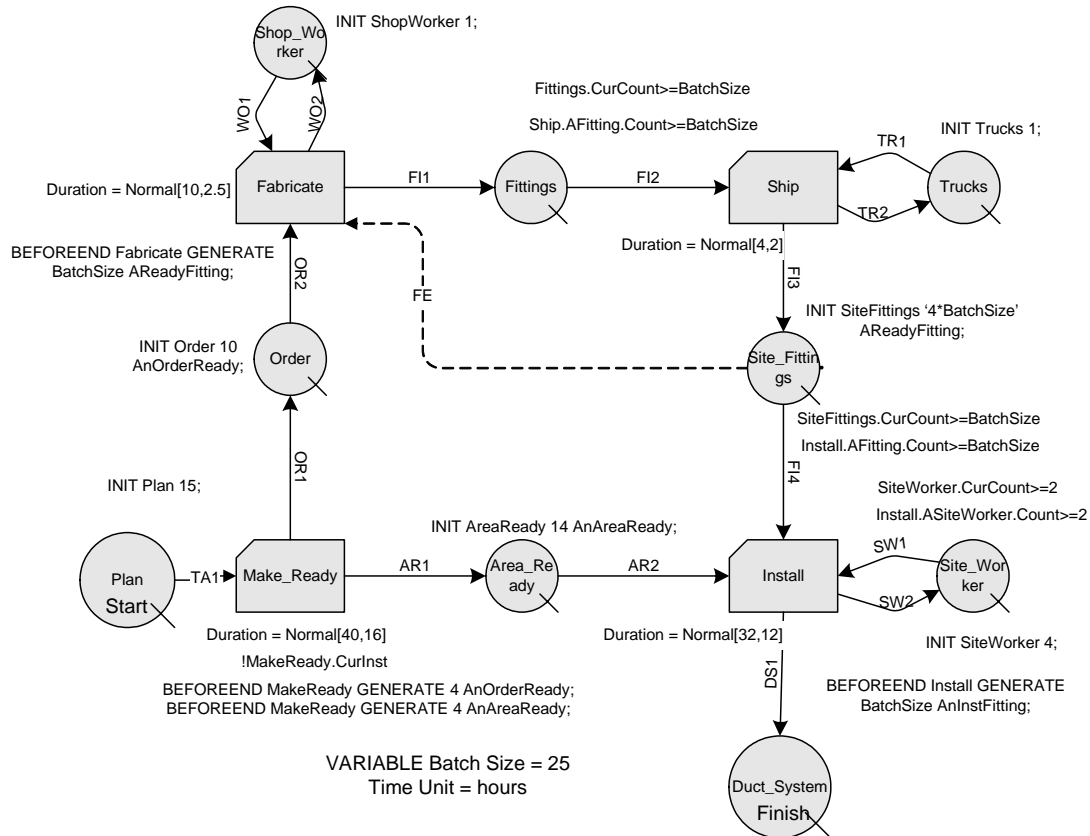


Figure 1: SMDSC simulation model in STROBOSCOPE

The queues Order, Area Ready, and Site Fittings were populated to help in the model warm-up (i.e., all activities have resources to process, successors do not have to wait until resources are processed by predecessors), and for consistency among the different scenarios studied. This warm-up emulates the real-life situation where work was left in the shop and on site at various stages of completion when the previous day or shift ended. Therefore, when the model starts, all queues but Duct System, have a buffer of resources to be used by the model's activities.

The batch size was chosen based on a time study described in Alves (2005). In that time study, the authors obtained the time the fabrication shop investigated took to fabricate a batch of similar size. The duration of the *Fabricate* activity was defined based on the same time study. Durations for *Make\_Ready*, *Ship*, and *Install* were obtained from interviews with mechanical contractors' personnel working as field superintendents and

on shipping departments. In the model, 1 worker in the fabrication shop supports 2 crews on the field. Approximately every 40 hours (5 days) the *Make\_Ready* activity GENERATEs 4 areas and 4 orders to be processed respectively by *Fabricate* and *Install*. Approximately every 10 hours, the worker in the fabrication shop completes 25 fittings (BatchSize), which takes roughly 4 hours to be shipped and distributed on the project site. Each field crew (2 Site\_Workers) takes about 32 hours (4 days) to install a batch of fittings, including supervision and material handling time.

## SCENARIOS SIMULATED

Five scenarios are defined to evaluate the outcomes of the model under different situations (Table 1). The metric evaluated in each scenario is the time the system takes to complete the project, which consists of the installation of 1,850 fittings. The variable BatchSize is fixed in the five scenarios (BatchSize=25 fittings). The seed 826375124 was used to simulate the different scenarios. The use of the same seed allows the models to be compared because every time they are simulated they will deliver the same results. If a seed had not been defined, STROBOSCOPE would randomly choose a number to start the simulation; therefore, results would vary from one run to the next.

In order to collect data for multiple runs, the COLLECTOR statement was used (Martinez 1996). Data for the queues was stored by STROBOSCOPE for multiple iterations. For each queue, STROBOSCOPE then calculated the mean ( $\mu$ ), standard deviation ( $\sigma$ ), minimum and maximum values based on the assumption that each set is normally distributed. These values can be used to analyze the buffer sizes until the project is completed. In order to facilitate data collection and the generation of graphs for multiple interactions, simulation code was included to collect data in 50-hour time intervals, instead of in every step of the simulation clock. The choice of this time interval for data collection does not jeopardize the authors' goal to illustrate how variations affect the system modeled because, rather than seeking precise numbers, their aim is to gain insights into this system's behavior.

Scenario A has deterministic durations represented by the mean durations of the activities shown in Figure 1. Scenario B has probabilistic durations, as shown in Figure 1. Scenario C uses the same probabilistic durations as scenario B but the size of orders and areas generated by the *Make\_Ready* activity is variable. That is, every time the *Make\_Ready* activity ends it generates a random integer number of areas and orders (same for both resources) between 2 and 6 (average = 4). In other words, scenario C has on average the same number of areas and orders generated as do A and B.

Scenarios D and E mimic the environment of mechanical contractors who fabricate ductwork before orders are requested by field personnel. They mimic a situation in which the *Make\_Ready* activity generates orders based on what has been finished by the detailing activity (not represented in the model). In this case, when the detailing activity ends, it generates drawings that are used to trigger fabrication. The batches of fittings are fabricated and stored in the Fittings queue, which represent the inventory in the fabrication shop. A batching activity was introduced in the model between the *Fabricate* activity and the Fittings queue so that the system can accumulate 10 batches of fittings before *Ship* transports them to their final destination. This batching activity represents the shipping of fittings to the field in large containers. In this model, it is assumed that a container can store two and a half weeks worth of fabrication work (i.e., 100 hours of

fabrication shop work = 2.5 weeks). Scenarios D and E mimic this environment using respectively deterministic and probabilistic durations.

In summary, Scenarios A, B, and C represent contractors for whom the *Make\_Ready* activity acts as a ‘pull’ mechanism to fabricate ductwork only when field installation needs it. Scenarios D and E represent the mechanical contractor for whom the *Make\_Ready* activity is represented by the detailing activity, in an earlier stage, to ‘push’ ductwork to be fabricated before it is formally requested by field installation.

Table 1: Scenarios used to simulate the model

Scenarios	Durations		Area/Order Size		Early Fabrication & Batching before Ship	
	Deterministic	Probabilistic	Fixed	Variable	Yes	No
A	✓		✓			✓
B		✓	✓			✓
C		✓		✓		✓
D	✓		✓		✓	
E		✓	✓		✓	

#### SCENARIO A – DETERMINISTIC

In Scenario A, the deterministic durations represent the best-case scenario in which the four activities shown in the model (Figure 1) always take the same time to be performed. Activities are performed without interruption, and there is no variability in the flows of inputs and outputs. In a construction site, this means that all resources necessary for performing activities are available and that there are no internal factors (e.g., variation in crew’s productivity rates) or external factors (e.g., supply of raw materials, interference with other trades) affecting the execution of tasks by the mechanical contractor. Scenario A is unrealistic in that there are no projects free of variation, but it is useful to calibrate one’s intuition about the system modeled. The final time for Scenario A is used as a benchmark for the analysis of the other models because it represents the time to complete the project in the best case scenario.

Figure 2(a) shows the result of the simulation model for Scenario A. The batches of fittings are fabricated and shipped to the construction site one by one by the *Ship* activity. Therefore, the buffer size at the Fittings queue is always 25 fittings (*Batch\_Size*) or less. The buffer at Site Fittings grows up to 750 fittings at time 704 and starts to decline steadily because no more fittings are fabricated after this time. In Scenario A, the project was completed (1,850 fittings installed) by time 1,184.

The volume of ductwork that accumulates at the construction site (Site Fittings) is unrealistic, as construction sites typically do not have space for such a large buffer of materials. However, this model illustrates that if there is no feedback between field installation (*Install*) and the fabrication shop (*Fabricate*) the buffer at the site can grow significantly. Ductwork also accumulates on site because *Fabricate* (10 hours) works faster than *Install* (32 hours); this illustrates that the fabrication shop can fabricate ductwork faster than the field can install it. That also suggests that *Install* can take

advantage of the faster pace of *Fabricate* by transferring some site operations to the fabrication shop. This transfer of operations could also help in distributing and balancing the load between field and fabrication shop.

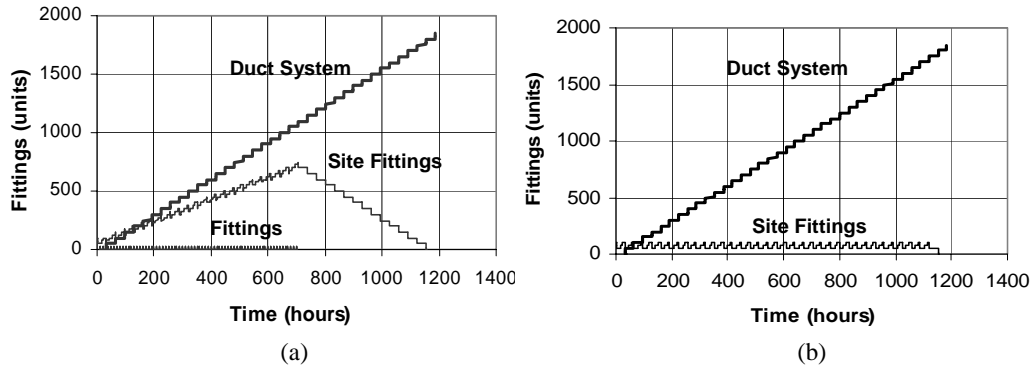


Figure 2: (a) Scenario A - deterministic durations;  
(b) Scenario A with feedback between Fabricate and Site\_Fittings

In order to reduce the buffer size at Site\_Fittings, the authors introduced a feedback link between Site\_Fittings and Fabricate (i.e., FE in Figure 1). The feedback FE triggers Fabricate every time the buffer of fittings at Site\_Fittings is smaller than or equal to 50 fittings. Figure 2(b) shows that with the feedback FE implemented, the maximum buffer size at Site\_Fittings is 100 fittings, as opposed to 750 fittings. The project is completed at time 1,184 as in the original Scenario A. Install did not run out of fittings for installation, even though the buffer size at Site\_Fittings was reduced.

Feedback FE is important because it regulates *Fabricate* and only allows it to produce more fittings when the buffer at Site\_Fittings reaches a minimum (i.e., 50 fittings). The definition of mechanisms such as the one represented by FE defines how the system is regulated. This example illustrates the importance of feedback links between different activities in the SMDSC. Other feedback links could be implemented to regulate buffer sizes in the SMDSC.

## SCENARIO B – PROBABILISTIC

In Scenario B, activities have probabilistic durations to represent the effects of variability in the execution of tasks. All activities deliver constant output but the time each activity takes to finish follows a normal distribution. In construction sites, variability in activity durations has different causes. One cause is the variation in the time it takes for the *Make\_Ready* activity to screen and remove activities' constraints and for it to generate output (e.g., material orders, areas ready to receive ductwork). Other causes are the level of difficulty of different jobs assigned to fabrication and installation crews and workers' skills set. These variations affect the buffer sizes in a production system because the times to process inputs are variable.

The results for a single iteration of Scenario B are compared to results of a single iteration for the other Scenarios investigated. The results for multiple iterations of Scenario B are used to evaluate the mean and standard deviation of the number of fittings installed at project completion. Figure 3(a) displays the results of the three queues (Fittings, Site\_Fittings, and Duct\_System) that store fittings for a single iteration. Figure 3(b) displays the results of the Duct\_System queue for multiple iterations.

Figure 3(a) reveals that the project was completed at time 1,220. The buffer size at the Fittings queue is 25 fittings or less, as the fittings are promptly shipped to the construction site after *Fabricate* ends (same as in Scenario A). The buffer at Site Fittings reaches a maximum of 600 fittings in different occasions between time 616 and 783.

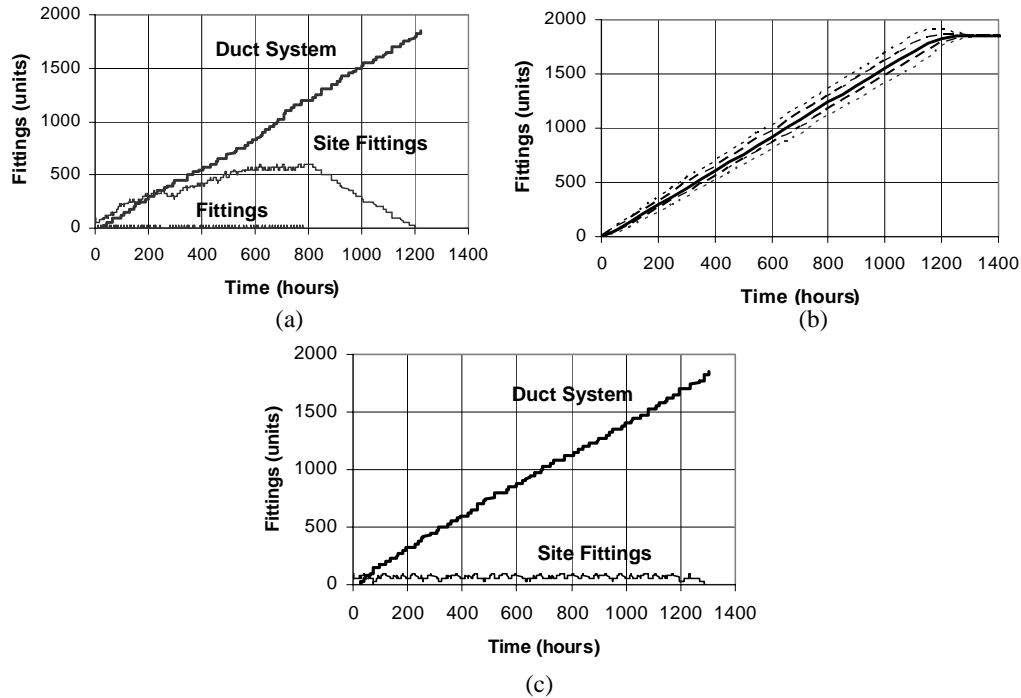


Figure 3: (a) Scenario B - Probabilistic durations (single iteration); (b) Scenario B – Probabilistic durations (100 iterations); (c) Scenario B – with feedback between Fabricate and Site\_Fittings

Figure 3(b) displays the results obtained from the model for multiple iterations. The solid line represents the average buffer size of fittings installed and stored in the Duct System queue for the multiple iterations. The dashed lines shown in Figure 3(b) represent one and two standard deviations of the values obtained through multiple iterations. In multiple runs of Scenario B, the project is completed on average at time  $1,184 \pm 50$  hours. By considering values within two standard deviations, the project could have finished as early as time 1,084 or as late as time 1,284. The difference in the completion time of multiple iterations of Scenario B ( $1184 \pm 50$  hours) when compared to Scenario A (1,184 hours) reveals the impact variability has on this production system. Moreover, the manifestation of variability could have caused the project to finish as early as time 1,084.

The authors also investigated the implementation of feedback FE (Figure 1) in Scenario B. Figure 3(c) reveals that the project was completed at time 1,304. The longer duration of the modified Scenario B, when compared to its original version, was observed because at time 76 Site Fittings runs out of fittings. Therefore, *Install* could not proceed at that time. This example illustrates the importance of acknowledging the effect of variability in the definition of buffer profiles. The buffer profile (i.e., minimum of 50 fittings at Site Fittings before new fittings are ordered) worked well for Scenario A (deterministic) but not for Scenario B due to the effects of variability in the modeled system.

### SCENARIO C – PROBABILISTIC DURATIONS + VARIABLE ORDER SIZE

Scenario C illustrates the effects of variability in the number of orders/areas generated by the *Make\_Ready* activity in addition to that caused by variations in activity durations. In all scenarios, except for Scenario C, one plan GENERATEs 4 orders (AnOrderReady) and 4 areas for installation (AnAreaReady). Based on these numbers and the simulation model constraints, in addition to the resources already in the queues in the beginning of the simulation, 15 plans are necessary to finish the project, which comprises the installation of 1,850 fittings. In Scenario C, orders generated by *Make\_Ready* vary in size between a minimum of 2 and a maximum of 6 orders and there is no predefined number of plans used to generate these orders.

Figure 4(a) shows the results obtained for Scenario C for a single iteration. The buffer size at the Site Fittings queue grows to 700 fittings at time 711. The buffer size at Fittings does not exceed 25 for the same reasons discussed for Scenarios A and B. A single iteration for Scenario C results in a project completion time of 1,224 hours which is slightly higher than the project completion times for Scenario A and B.

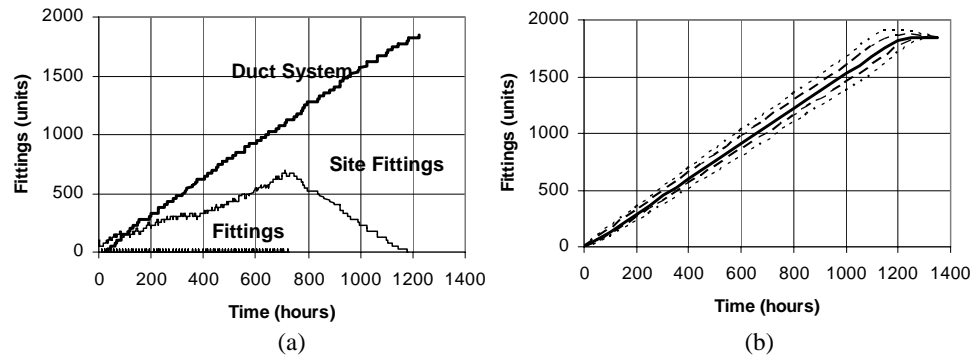


Figure 4: (a) Scenario C – Probabilistic durations + variable order size (single iteration);  
(b) Scenario C – Probabilistic durations + variable order size (100 iterations)

The analysis of multiple iterations for Scenario C (Figure 4(b)) reveals that the time the model takes to complete the project is  $1,199 \pm 53$ . Due to the variability in order sizes Scenario C's performance is worse than Scenario B's (both used probabilistic durations).

### SCENARIO D – DETERMINISTIC DURATIONS + BATCH BEFORE SHIP

Scenario D uses the same deterministic durations used in Scenario A. However, in this scenario fittings are shipped to the construction site in batches of 250 fittings (i.e., 10 times the Batch\_Size of A). The *Make\_Ready* activity represents the detailing activity, which generates details (in this case orders) used to fabricate fittings in anticipation of the field demand.

Figure 5 shows the results obtained for Scenario D. The mechanical contractor in Scenario D has to have enough space available at the construction site or elsewhere to store a large buffer of fittings. The maximum buffer size in the shop (Fittings) is 250 fittings, 10 times larger than in the previous models due to the batching requirement for shipping fittings to the construction site. The buffer size on the construction site (Site Fittings) grows up to 800 fittings at time 704. The buffer steadily gets smaller after all orders have been shipped and installation progresses in a smooth fashion. The project is completed at time 1,224, which is later than Scenario A's. Scenario D illustrates one of the effects large batches have in production systems (i.e., lead time increase). The

batching requirement resulted in a delay in the time to complete the project even though the duration of the *Ship* activity (for a large shipment) was assumed to be the same as in Scenario A.

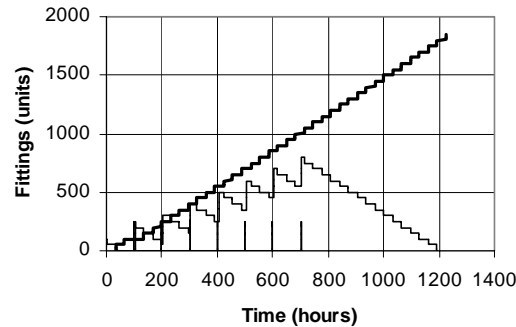


Figure 5: Scenario D – Deterministic durations + batching before Ship (single iteration)

### SCENARIO E – PROBABILISTIC DURATIONS + BATCHING BEFORE SHIP

Scenario E has the same characteristics of Scenario D, except that it uses probabilistic durations for activities. Figure 6(a) shows the results for a single iteration of Scenario E. The buffer size in the fabrication shop (Fittings) grows up to 250 fittings and the buffer size on the construction site (SiteFittings) grows up to 700 fittings at time 740. The project is completed at time 1,275, about 50 hours after its deterministic version. Figure 6(b) shows the results for multiple iterations of Scenario E. The figure revealed that the project is completed on average around time  $1,243 \pm 52$ . This model illustrates the effect that variability coupled with batching requirements has in lead times. Scenario E requires the most time to complete the project when compared to all other Scenarios.

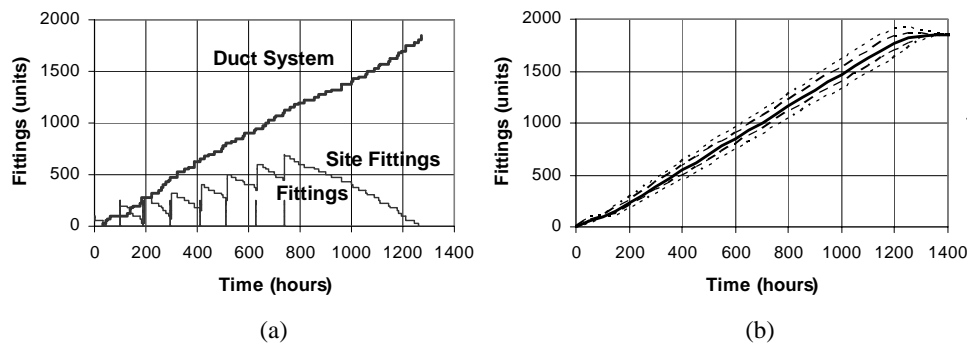


Figure 6: (a) Scenario E – Probabilistic durations + batching before Ship (single iteration);  
(b) Scenario E – Probabilistic durations + batching before Ship (100 iterations)

### DISCUSSION OF SIMULATION MODEL RESULTS

Analysis of Scenarios A through E revealed the effects variability in durations and order sizes, as well as batching requirements have on the time to complete a project. Scenario A illustrated how the system modeled behaved in the absence of variability and delivered the best result (project completed in time 1,184 hours). As variability and batching are added to the models, the project completion times grow as does the corresponding uncertainty (measured by  $\sigma$ ). Scenarios D and E, which illustrated a ‘push’ system with large shipping batches, took the longest time to complete because of the batching

requirement. The project duration increased as more variability and batching requirements were added to the system.

These models did not investigate the matching and sequencing problems, and the impact standardization has on project performance. As discussed by Tommelein (1998, 2006), these problems can change the level of complexity of projects and have an impact on projects' completion time. However, they illustrated the impact of variability in production systems and the importance of feedback between activities to prevent the growth of buffers (i.e., feedback between *Fabricate* and *Site Fittings*). Insights gained from the model can be used to evaluate decisions on production systems' design and particularly buffer sizing. The development of this model highlights the importance of having reliable data to use when designing production systems and simulation models thereof. In order to develop the model, the authors needed basic information about activities pertaining to the delivery of sheet metal ductwork. Mechanical contractors and researchers in general need to invest more effort into gathering more representative sets of data for use in production-system design.

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