SIMULATION OF BUFFERING AND BATCHING PRACTICES IN THE INTERFACE DETAILING-FABRICATION-INSTALLATION OF HVAC DUCTWORK

Thais da C.L. Alves[1] and Iris D. Tommelein[2]

ABSTRACT

Modeling the supply chain for heating, ventilation, and air conditioning (HVAC) ductwork presents challenges at different stages because of the nature of the product involved. Metal coils and sheets can be quantified in terms of material, gauge, width, and weight. However, when they are transformed into ducts and fittings, quantification becomes more complex. First, some sheet metal companies measure their throughput in terms of mass of sheet metal per time and not in units of fittings and ducts per time, regardless of the level of complexity to fabricate these parts. Second, fittings and ducts have some of their characteristics specified but not all of them; there is a quite high degree of customization for both products. To improve understanding of this production process, this paper investigates the activities in the interface detailing-fabrication-installation of HVAC ductwork. The simulation software STROBOSCOPE is used to mimic different scenarios, including the behavior and outputs of these activities as well as the interaction among them. The data used to develop this model comes from an ongoing study of HVAC contractors. The model specifically deals with variations in batches and buffers sizes and their impact on system throughput, work in process, and lead times for a pull system. This paper presents more detail on inventory buffers; capacity, time and plan buffers are not elaborated on. Analysis of different scenarios provides insights as to how lean concepts can be used to trigger improvements in the interface investigated.

KEY WORDS

Buffer, batch, sheet metal duct work, HVAC system, mechanical contractors, simulation

[1] Ph.D. candidate, Engineering and Project Management Program, Department of Civil and Environmental Engineering, University of California at Berkeley, thaiscla@berkeley.edu

[2] Professor, Engineering and Project Management Program, Department of Civil and Environmental Engineering, 215-A McLaughlin Hall, University of California, Berkeley, CA 94720-1712, 510/643-8678, FAX 510/643-8919, tommelein@ce.berkeley.edu

INTRODUCTION

Research to date indicates interest of the research community in the study of several aspects of buffers in construction. Buffers are resource cushions, i.e., money, time, materials, space, etc., used to protect processes against variation and resource starvation. Previous studies addressed how buffers are or should be used in different types of construction projects (Howell and Ballard 1996, Horman and Kenley 1998); how buffers are generated in production systems (Tommelein 1998, Tommelein et al. 1999, Tommelein and Weissenberger 1999); and how capacity buffers can be used to reduce waste and improve project performance (Horman 2001).

The AEC industry uses several practices to keep workers, machinery, and equipment busy. Indeed, this industry is obsessed by the idea that all resources should be kept busy at all times, even when they are performing tasks that are not directly needed to advance a project. In order to achieve this, large buffers are commonly found in construction. The use of buffers in production systems stems from the desire to optimize labor and machine utilization as well as from the acknowledgement that uncertainties exist in the supply chain (e.g., Tommelein and Weissenberger 1999). However, as discussed in this paper, the use of buffers throughout a supply chain to increase its efficiency may also have unintended consequences.

The need to protect production in construction against variation in the supply chain also stems from several obstacles related to uncertainty. *"Large buffers reduce the need for reliable planning as they allow some work to get done despite uncertain flows. Large buffers allow flexibility and mask the extent of uncertainty because current planning systems fail to control work flow* (Howell and Ballard 1996, p. 41)." Therefore, the definition of buffer profiles, i.e., type, location, and size, in a supply chain is an important aspect for revealing system inefficiencies and ultimately for achieving continuous flow.

Unveiling the rationale behind the definition of buffers by construction companies and studying their impact on supply chains is the main goal of a larger research study conducted by the authors. The simulation model presented in this paper is only a part of this research. The model was built to enhance the authors' understanding of the effects buffers and batches have on the outputs and lead times of the supply chain of sheet metal ducts and fittings.

In this paper, the authors simulate the behavior of the supply chain for HVAC sheet metal ducts. Buffers and batches are explicitly modeled and their impact on the overall supply chain is discussed. Specifically, the detailing, fabrication, and installation of sheet metal ducts and fittings for HVAC systems by mechanical contractors are discussed. Mechanical contractors have multiple capabilities pertaining to HVAC, plumbing, piping, and installation of related equipment such as chillers, fans, boilers, and pumps. Design, fabrication, installation, and maintenance can all be performed by a single contractor. Thus, design-build mechanical contractors play an important role in the supply chain for HVAC systems because one single supplier may be in charge of almost the entire life cycle of the HVAC system. The study of this supply chain is relevant because researchers are able to study one single entity, i.e. the mechanical contractor, and the effects its decisions about buffers have in several stages of this supply chain.

TYPES OF BUFFERS

A production system has to be buffered against variability in order to avoid loss of throughput, wasted capacity, inflated cycle times, larger inventory levels, long lead times, and poor customer service (Hopp and Spearman 2000). *"While there is no question that variability will degrade performance, we have a choice of how it will do so. Different strategies for coping with variability make sense in different business environments."* (Hopp and Spearman 2000, p. 295). According to Hopp and Spearman (2000, p.295), three types of buffers protect a production system against variability, namely (1) inventory, (2) capacity, and (3) time. Adopting a management perspective, Ballard and Howell (1995) introduce a forth type the plan buffer. We further elaborate on buffers in this section to help the reader understand how the main types of buffers work and what their importance is in a production system.

1. Inventory: Physical inventories may be categorized according to their position and purpose in a supply chain. "Raw materials, work-in-process, and finished goods are terms used to describe the position of the inventory within the production process. Buffer stocks, safety stocks, and shipping stocks are terms used to describe the purpose of the inventory" (Lean Enterprise Institute 2003).

2. Capacity: In construction, consideration of the environment (i.e., site access and conditions) plays a major role in defining how much capacity should be allocated to a certain project. Some units to express capacity may include number of available hours of resources (Buffa 1969) and space required to perform operations (Tommelein and Zouein 1993). Another consideration to evaluate capacity strategies is the 'make or buy' decision. If a mechanical contractor decides to outsource fabrication of the parts it is able to fabricate, it may be giving up part of the power it has in terms of process control and/or part of its profits. Conversely, outsourcing may be freeing up capital that would otherwise be committed to production.

3. Time: Time buffers are used in project management. Goldratt (1997) suggests that estimates for a project usually have extra time embedded in them to deal with variations. The fact is that people always use this extra time, in accordance to Parkinson's Law, which says that a task will take as long as the time allotted for it to be done. Goldratt stresses that the way time buffers are currently used is wrong: instead of being used to deal with uncertainties they are always used as a part of the time to perform a task. In Critical Chain Project Management (Goldratt 1997), time buffers are used to manage schedules. Also, the concept of float in the Critical Path Method may be seen as some sort of time buffer. It provides flexibility to define the start dates for activities, without delaying project completion.

4. Plan: Plan buffers are "inventories of workable assignments" (Ballard and Howell 1995). Plan buffers are used when the main tasks planned cannot be performed, and the crews are available to perform alternative tasks indicated in the plan buffer.

The capacity buffer is used by mechanical contractors to deal with variations in demand, and its function and implications on the supply chain are discussed in the next section. The model presented in this paper suggests that in spite of mechanical contractors using quite large capacity buffers in their fabrication shops (Alves and Tommelein 2003), managers still buffer their tasks with inventory buffers for the sake of achieving high levels of resource utilization.

SUPPLY CHAIN OF SHEET METAL DUCTS AND FITTINGS

The lack of work structuring of design and construction tasks and the use of non-value-adding ductwork documents are but two problems encountered in the interface between mechanical design and construction (Miles and Ballard 2002). These problems contribute to the difficulties project managers encounter in scheduling the mechanical crew's work and in supplying ducts and other parts from fabrication shops to the site. Therefore, managers typically plan for buffers at the interfaces between tasks to decouple operations (Howell et al. 1993).

Contractors who design, fabricate, and install sheet metal ducts and fittings for HVAC systems, deliver not only a product but also a service. This is important to note because it determines the way the supply chain for this product is set up. The products fabricated, ducts and fittings, can be stocked up, but only to a degree because ducts are made-to-order and parts are usually large, so they are difficult to store. The services (design and installation) cannot be stocked up. Parts can be assembled and tested separately but the entire work must be put together only at its final location. Moreover, the customer has a high level of input in the process; the design is custom-made according to customer's specifications and it is often allowed to change even during the construction phase to accommodate customer's needs. In distinguishing the delivery of a product from a service, Schmenner (1993, p. 16) notes: *"Frequently, the consumption of a service is nearly simultaneous with its production. Services cannot be inventoried for use later on. This fact has some serious implications for capacity choice and capacity management in a service business. (...) Demand irregularities place a tremendous burden on a service operation to be flexible."*

Because mechanical contractors cannot inventory all the outputs of their work, which are part products and part services, they often rely on capacity buffers to be flexible and quickly respond to variations in demand (Alves and Tommelein 2003). The use of capacity buffers allow contractors to start the work on the fabrication based on site demand. This resembles a pull system, which is a "*system that authorizes the release of work based on system status*" (Hopp and Spearman 2000, p. 340).

Based on the characteristics presented, one can advocate that the pull system will help to effectively manage this supply chain because its products, to a large extent, cannot be kept on inventory. Therefore, the detailing and fabrication of ducts should be triggered only when the level of uncertainty regarding the types of parts needed is minimal, the pre-requisite tasks are done, and when these parts can arrive on site and installation can proceed almost immediately.

However, the use of a pull mechanism does not preclude the use of buffers in the system. Zero inventory can be only an ideal for lean production; without work-in-process a production system has no throughput. Different production rates, levels of uncertainty, and requirements for activities require that buffers be used to assure a continuous flow of work. However, sizing the buffers between these activities is a challenge because participants in this supply chain may not be willing to share information about their production capabilities nor be able to see the impact their actions have throughout the entire supply chain, e.g., the beer game by Jay Forrester. This makes the modeling of the HVAC supply chain under a pull system very useful to understanding what impact pull may have in construction systems.

SIMULATION MODEL TO MIMIC BATCH AND BUFFER ALLOCATION THROUGHOUT THE HVAC PRODUCTION SYSTEM

Waste and other problems that plague the construction industry are in part the result of local optimization efforts pursued by individual firms (Vrijhoef and Koskela 1999). This is aggravated by the lack of communication and transparency among supply chain participants in construction (Tommelein 1998). Efforts aimed at increasing transparency and the understanding of how systems work in the AEC industry are welcomed. According to Tommelein (1998, p. 287-288), "(p)articipants who can 'see' the other's needs, can better plan to accommodate them." Therefore, anticipating the problems that may hamper a project and properly preparing the production system to deal with them is likely to improve a firm's competitiveness. It may reduce the firm's operating expenses and increase its flexibility to quickly respond to changes in the environment.

The software used to model and simulate the supply chain for HVAC ducts and fittings is the STROBOSCOPE system, which "*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).

REPRESENTATION OF HVAC SUPPLY CHAIN USING STROBOSCOPE SYMBOLS

Assumptions and limitations of the model

In order to develop the simulation model, the authors made simplifications and assumed some parameters based partially on interviews with mechanical contractors, and partially on the authors' own understanding of the activities represented.

The mechanical contractor's work as represented here in the supply chain for HVAC sheet metal ducts and fittings deals only with the production of ducts and fittings. Its scope of work comprises detailing ducts on site and at the fabrication shop, the fabrication of ducts in an in-house shop, and the installation of ducts and fittings on site. The work of other trades that precede the installation of HVAC ducts and fittings was not modeled in detail, even though they release work spaces so that HVAC installers can perform their work.

Durations were defined based on conversations with mechanical contractors' personnel and are represented in days. Each work day has 8 hours and a week has 5 work days; breaks, weekends, and holidays are currently not represented. Mechanical contractors may be able to work on different shifts and on weekends. Work on extra shifts would reduce parts lead times while creating extra costs related to paying the work force.

The size of buffers and the relationships between them were defined based on the authors' assumptions about the different activities represented. All parts are assumed to be equal and are detailed, fabricated, and installed on a first-in-first-out (FIFO) basis. The number of resources necessary to detail, fabricate, and install parts is the same for all parts. A relationship is assumed between buffers in the system and the activities they precede. Figure 1 shows the activities (rectangles) and the buffers (triangles) between them. Buffer size (BufSize) is a variable defined in the model that influences the amount of work-in-process and throughput of the system as well as the lead time to install a defined number of ducts.

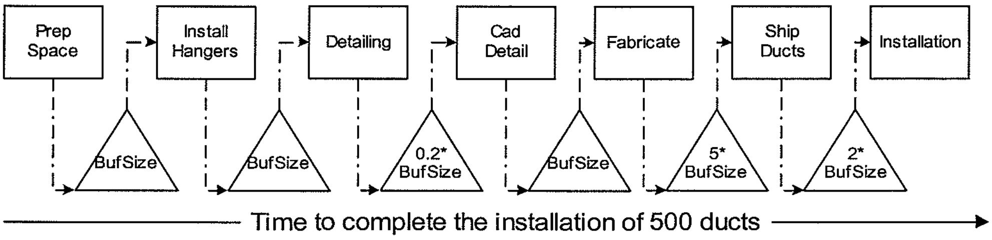

Figure 1: Minimum buffer sizes between activities.

For instance, between Fabricate and the Shipping of Ducts (ShipDucts), the buffer is five times the size of the 'BufSize'. This means that the shipping activity can only start after '5*BufSize' is available. The large buffer between these two activities is intended to deal with the matching problem. The shipping activity may have to be delayed until different parts required for a certain area are put together in a single batch to be sent to the construction site on a single truck.

The buffers between the activities represented may be understood by some as batching requirements for an activity to start. However, the activities modeled may start any time in a project; they do not have a pre-defined economic lot size of work. *"Batching means processing products in lots, rather than by the piece, and it is usually done in order to avoid incurring the cost associated with repeated setups. Buffering means accumulating several units of input to a process prior to starting that process, and it is usually done in order to maximize the processor's utilization rate or to avoid having the processor run out of inputs (to 'starve')"* (Alves and Tommelein 2003).

The sequence of activities required to detail, fabricate, and install sheet metal ducts and fittings was simplified. For instance, Bhattal (2002) developed a model that illustrates most of the activities required to fabricate a duct. Holzemer et al. (2001) analyzed in detail the material and information flows for fabrication and installation of HVAC ducts. However, in the simulation model presented herein, fabrication is represented as a single activity that bundles all the steps needed to fabricate a duct. The present model illustrates the relationships between different processes in the context of a broader supply chain and not only the fabrication process. The authors understand the significance of the fabrication process for this supply chain and they are working on a model to better describe this process.

Finally, it is assumed that the trucks used to ship ducts to the construction site can only transport at most 40 ducts per trip. Spaces, details, and ducts have a 1:1:1 relationship in the model, i.e., one space is used to produce one detail, which is used to fabricate one duct. The relationship between cut sheets and ducts is 1:5, i.e. one cut sheet has five ducts detailed on it.

Simulation model

Figure 2 shows the simulation model for the supply chain of sheet metal ducts for HVAC systems, including durations, amount of resources, relationships between activities, and some commands used in the STROBOSCOPE source code. The model has five main subsystems namely (1) Site Work, (2) Preparation of Space, Site Detailing, (3) Faxing Cut Sheets, Shop Detailing, Fabrication, (4) Shipping of Ducts, and (5) Installation.

The simulation starts when the activity Preparation of Space (PrepSpace) generates 10 Ready Spaces (AReadySpace), which are work areas ready for the mechanical crews to start working. Every time this activity completes it releases to the subsequent activity 10 Ready Spaces, this number is not a function of the BufSize variable. Crews that install hangers wait until at least a BufSize of Work Spaces is available to start working, and when their work is over, they release a BufSize of Duct Paths (ADuctPath) to Detailing. Install Hangers (InstallHangers) is the activity that triggers the order for ducts. Once hangers are installed, the positions of ducts and their characteristics are defined and the site detailer (Detailer) can prepare the cut sheets that represent orders, and fax them to the fabrication shop. Five ducts are detailed on each cut sheet, which is faxed to the fabrication shop to be Detailed on CAD (CadDetail).

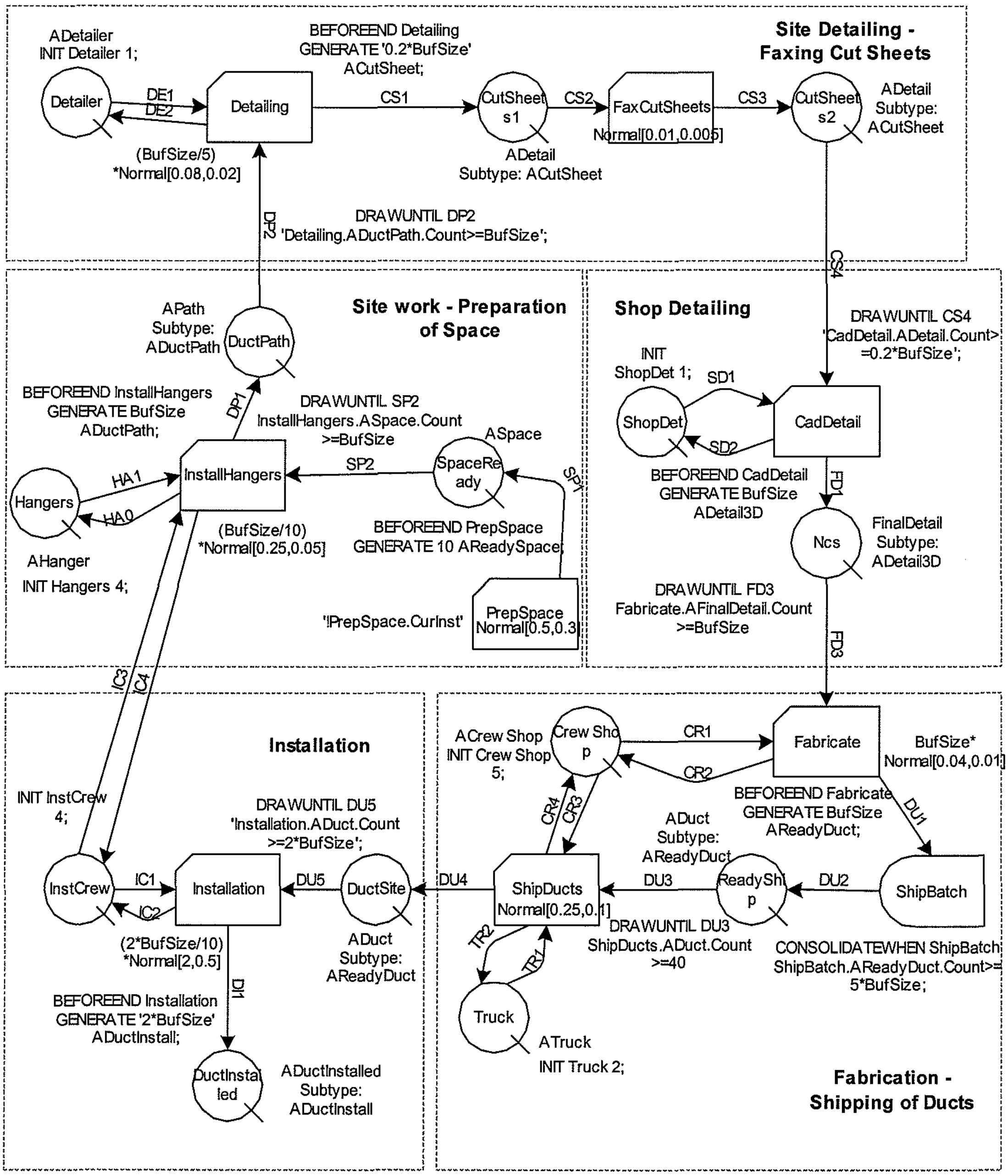

Figure 2: Simulation model for the HVAC Sheet Metal supply chain (Detailing – Fabrication - Installation).

The Shop Detailer (ShopDet) waits until 0.2*BufSize of Cut Sheets (ACutSheet) accumulates before they can be detailed on CAD. Then, the Detailing on CAD (CadDetail) is triggered and it generates a BufSize of 3D details (ADetail3D), which is sent directly to the Fabricate activity. After ducts are fabricated, they are sent to a staging area (ShipBatch), which consolidates a number of ducts equal to 5*BufSize before they are released to the queue that holds Ready to Ship Ducts (ReadyShip). The Shipping activity (ShipDucts) draws ducts from the Ready to Ship Ducts queue and uses two trucks that can only transport 40 ducts per trip per truck. Finally, Installation starts only after 2*BufSize of Ready Ducts (AReadyDuct) have accumulated on Site (DuctSite) and it generates the same number of ducts installed. These are sent to the queue that holds installed ducts (DuctInstalled), and represent the final output of the modeled system.

ANALYSIS OF RESULTS

The model allows for the study of variations in batches and buffers sizes and their impact on the system output, work in process, and parts lead times for a pull system. The objective of the model is to illustrate how the choice of the inventory buffer between activities impacts the system output and the parts lead times. In order to evaluate the impact the assigned buffers have on the system modeled, simulations were run with different values for BufSize, i.e., 20, 50, 100. Simulation data including the accumulated number of units throughout time (days) received by queues that succeed specific activities in the model was analyzed. Results represent the output for the installation of 500 ducts in a single simulation run. Multiple runs will be simulated at a later time in order to obtain statistical data (e.g., see Arbulu et al. 2002 for a similar study that analyzes deterministic and probabilistic models on installation of pipe supports). Table 1 shows the activities and queues analyzed.

Table 1: Activities and queues analyzed

Activity	InstallHangers	Detailing	CadDetail	Fabricate	ShipDucts	Installation
Queue	DuctPath	CutSheets1	Ncs	ReadyShip	DuctSite	DuctInstalled

Figure 3 shows the results for a BufValue equal to 20 units. Most activities progress in a smooth fashion. However, the DuctSite and DuctInstalled curves reveal the impact of two constraints: the maximum number of ducts transported by trucks (40 units) and the minimum number of ducts necessary to trigger the Installation activity. The combination of these two constraints and the batching activity, which occurs on ShipBatch, result on a curve that progresses on steps, and delays the final installation of ducts, which ends around day 35.

Figure 4 shows the results for a BufSize equal to 50. The accumulated number of units on each queue again shows a smooth progression for the first four queues (DuctPath, CutSheets1, Ncs, and Ready Ship). However, the impact of larger buffers required throughout the system and the impact of the batching activity amplified the difference between the curves. In two occasions, DuctSite and DuctInstalled had to wait for more than 10 days to receive the next shipment of ducts and the next batch of ducts installed, respectively. The last batch of ducts is installed around day 40.

Figure 5 presents the results for a BufSize of 100. DuctPath, CutSheets1, and Ncs accumulated units progress in a smooth fashion, starting around day 7. The queues ReadyShip, DuctSite, and DuctInstalled started receiving ducts more than 25 days later, around day 35 because of the effect of batching in ShipBatch and the reduced capacity of trucks to transport ducts to the site. On time 35, we observe that 500 ducts were available in ReadyShip to be shipped to the construction site, but trucks can only transport 40 ducts. Therefore, the content of DuctSite grows in a steep fashion between time 35 and 40. Finally, the installation of ducts starts only after a buffer of 200 ducts is available, after day 35 and the installation of the 500 ducts ends around day 60.

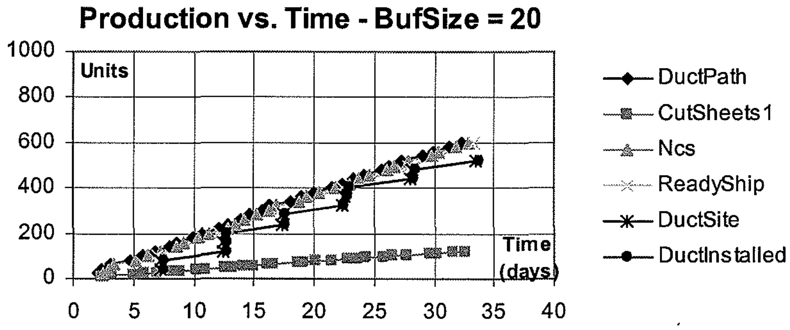

Figure 3: Units produced vs. time, for selected activities in the model – BufSize = 20 units

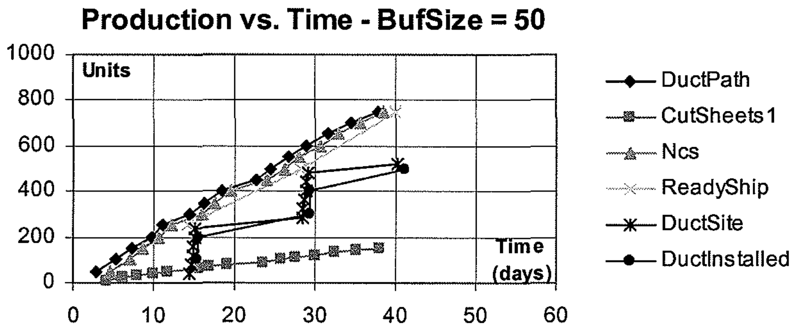

Figure 4: Units produced vs. time, for selected activities in the model – BufSize = 50 units

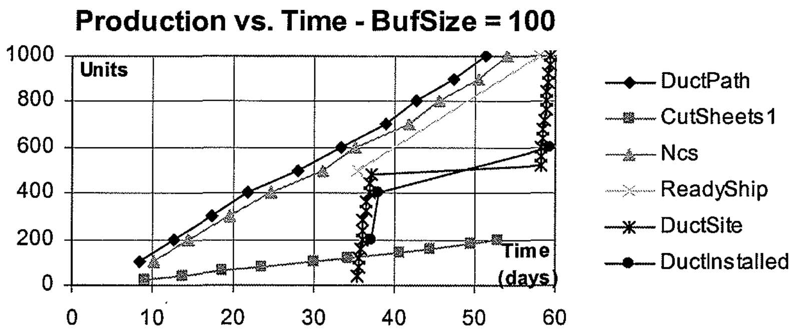

Figure 5: Units produced vs. time, for selected activities in the model – BufSize = 100 units

DISCUSSION

Varying the BufSize variable directly impacts the time it takes for the first group of ducts to be installed on site. Table 2 shows the time the first and the last batch of each product, in each of the queues evaluated, was created for different values of BufSize.

Table 2: Simulation time and units produced for different values of the variable BufSize.

		BufSize = 20		BufSize = 50		BufSize = 100	
Event	Product	SimTime (days)	Units	SimTime (days)	Units	SimTime (days)	Units
First	Path	2	20	2.99	50	8.34	100
Last	Path	32.27	600	37.68	750	51.43	1000
First	Detail	2.33	4	4.13	10	9.21	20
Last	Detail	32.6	120	38.07	150	52.97	200
First	CAD detail	2.59	20	4.71	50	10.22	100
Last	CAD detail	32.82	600	38.46	750	53.9	1000
First	Fabricated duct	7.02	100	14.23	250	35.33	500
Last	Fabricated duct	33.3	600	40.11	750	57.95	1000
First	Shipped duct	7.24	40	14.49	40	35.42	40
Last	Shipped duct	33.48	520	40.29	520	59.36	1000
First	Installed duct	7.51	40	15.32	100	37.17	200
Last	Installed duct	33.74	520*	41.04	500*	59.37	600*

*Final numbers for the last batch of installed ducts differ because the model collects output data according to the variable BufSize and its impact on the system's activities, and because of the termination condition for the simulation. The simulation runs until the activity Installation has finished and delivered a number of ducts that is equal or greater than 500.

Table 2 reveals that the time the first batch of 20 units of path, for BufSize = 20, took to become installed ducts was about 5.5 days. In other words, the first 20 ducts were ordered on day 2 and were installed on site on day 7.5, resulting in a lead time of 5.5 days. In the second scenario when BufSize = 50, at time 2.99 the first 50 ducts were ordered, and they were installed more than 10 days later, on time 15.32. For BufSize = 100, the first 100 ducts were ordered on time 8.34 and installed on time 37.17.

The influence of the batching after the ShipBatch consolidator is illustrated in Table 2 (gray lines) by the difference between the time the first batch of CAD detail is prepared and the time the first group of fabricated ducts is available to be shipped to the site. The higher the BufSize value the longer it takes for the batch to be assembled and released to the next activity. This means that if managers try to pull on their supply chain, but the size of buffers between activities is too large, some advantages of the pull system are lost. In this case, the supply chain loses its capacity to quickly respond to variations in demand because buffers between activities are too large. This also amplifies the importance of first reducing the level of uncertainty related to activities so that buffers can be reduced and the whole system can be more effective.

Finally, the time it took for the model to install 500 ducts grows as the BufSize variable grows. This is illustrated on the last line of Table 2. Some people may think that increasing buffer sizes will improve system performance and increase system reliability. However, while attempting this, they are in fact sacrificing the system's lead times and increasing the levels of work in process throughout the system.

CONCLUSIONS

The model presented here is work in progress. As simple as it is today, it documents interactions between stakeholders and activities in the supply chain and reveals how the definition of buffers and batch sizes impacts the system's outputs and lead times. The authors did not yet investigate the effects of allocation of capacity, time, and plan buffers in this model. The different values assumed by the variable BufSize alter the physical inventory buffers and the production rates to reflect an increase on the number of units turned out by each activity.

The increase in the variable BufSize in this supply chain reflects a desire to have larger buffers to deal with the level of uncertainty participants face on their work as part of a supply chain. Simulation results reveal that if supply chain participants need large piles of inventory between activities, lead times and work in process increase and the system's throughput decreases. Thus, contractors are sacrificing lead times and inventory levels in their systems by trying to improve the reliability of their systems using this approach. The implementation of a pull system fails with an inadequate definition of buffer's profiles.

Based on the model presented, the authors want to emphasize the important role mechanical contractors can play in improving the performance of the supply chain for sheet metal ducts. They are in charge of several consecutive steps in this supply chain and may be able of reap benefits from the better buffer management.

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