BUFFERING AND BATCHING PRACTICES IN THE HVAC INDUSTRY

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ABSTRACT

This paper discusses batching and buffering practices in the Heating, Ventilating, and Air-Conditioning (HVAC) industry based on a literature review and an on-going investigation of mechanical contractors in charge of designing, fabricating, and installing made-to-order ductwork systems. Batching practices affect or create buffers in production systems whether intentional or not. Buffers in production systems may be characterized by location, size, product mix, criticality, etc. Here, the focus is specifically on the location of buffers that result from batching and buffering practices in the production system for duct fabrication and installation. These practices are influenced by organizational issues, production capabilities, labor union regulations, product characteristics, 'received traditions,' and local optimization objectives. They are also influenced by the difficulty of forecasting the available capacity and production demand in terms of labor-hours and product mix. A rule of thumb for contractors that perform work in the ceiling space of a building, as is needed for HVAC duct, is "the first one to get in wins." Therefore, these contractors have to be agile in turning out parts to the construction site in order to avoid major changes in their design, fabrication of parts, or installation sequencing. All these characteristics and influences interact in a dynamic way and thereby contribute to the batching and buffering practices that have become custom and accepted. While these practices may meet local optimization criteria, they also embed a lot of waste in the production system at large. The purpose of this paper is to elucidate current practices so as to promote understanding of the system's characteristics and development of metrics to optimize system performance at a more global level.

KEY WORDS

Buffer, batch, inventory, sheet metal, duct work, HVAC system, specialty contracting, mechanical contractor.

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INTRODUCTION

Ongoing research described in this paper aims to characterize batching and buffering practices in the Architecture, Engineering, and Construction (AEC) industry. Specifically, the authors have been studying mechanical contractors and their delivery systems for HVAC ductwork. Opportunities for performance improvement in this industry were suggested by ‘lean’ practitioners and researchers including Skinner (1999), Holzemer et al. (2000), Miles and Ballard (2002), Miles et al. (2002), and Bhattal (2002). In line with that work, the purpose of this paper is to elucidate current practices so as to promote understanding of the system’s characteristics and development of metrics to optimize system performance at a more global level. The authors do not elaborate on a theory for buffering or batching, but rather review basic concepts and then illustrate batching and buffering practices in the HVAC industry. For a more in-depth discussion about buffers and batches the reader may check Shingo (1988), Schmenner (1993), and Hopp and Spearman (2000).

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’). Many batching and buffering practices within and across organizations have gradually evolved over time. They have become custom and accepted—what Schmenner (1993 p. 379) calls ‘received tradition.’ While these practices may meet some local optimization criteria, they often are myopic and embed a lot of waste in the production system at large. Despite ‘received tradition,’ batching and buffering practices can be defined and controlled by production managers.

Batching practices affect or create buffers in production systems whether intentional or not. For instance, “(t)he need for large serial batch sizes is caused by long set up times. Therefore, the first priority should be to try to reduce setup times as much as economically practical (Hopp and Spearman 2000).” If set ups are difficult to perform and time consuming, companies would rather produce as much as they can and think they will need of one type of product before they change to the next one. This practice generates physical inventory, i.e., parts that are not needed as soon as they are produced, throughout a production system.

Schmenner (1993, p. 247) stresses the function of different types of inventory as a means of buffering production. Raw materials inventory buffers production against the effects of unreliable delivery of raw materials; work-in-process shields production from unreliable delivery of materials from other operations in the production process; and finished goods inventory protects the company against uncertainty in consumer demand.

“Managing flows in construction is more difficult than in the production phase of manufacturing because there is uncertainty both in what is to be accomplished and in the provision of requirements for assembly” (Howell and Ballard 1994). Shielding production from the undesired effects of uncertainty and interactions can be achieved by properly allocating and sizing buffers throughout the production system (Schmenner 1993, Howell et al. 1993, Ballard and Howell 1995).

Ballard and Howell (1995) suggest plan buffers, i.e., “inventories of workable assignments”, and schedule buffers, i.e., “inventory of stuff and time”, as means of using buffers to achieve a Just In Time (JIT) type of system in construction. They discuss different rules and suggest as to where and how "plan" and "schedule" buffers should be located in a system.

Their first step towards achieving construction JIT is to attack the causes of uncertainty in a system before eliminating schedule buffers. Otherwise, without the protection of buffers, the system may be vulnerable to the effects of uncertainty. Meanwhile, schedule buffers should be judiciously sized and located in the system. Their next step is to progressively substitute schedule buffers by plan buffers. In other words, they advocate that the planning system little by little should be able to keep a backlog of workable assignments in order to achieve and maintain a steady and reliable flow of work. In summary, the proper management of buffers—plan and schedule buffers—is crucial for leveraging the performance of construction processes because buffers can shield production from uncertainty and help with achieving a more reliable flow of work.

Different factors are critical to managing batches and buffers in a production system namely location, size, product mix, criticality, etc. Here, the focus is specifically on the location of buffers that result from batching and buffering practices in the production system for duct fabrication and installation.

BASIC CONCEPTS

VARIABILITY AND BATCHING

Hopp and Spearman (2000) distinguish two types of variability: (1) bad variability is related to planned and unplanned outages, quality problems, operator variation, among others; (2) good variability refers to an intended introduction of variability in a system as a form of leveraging the system's ability to match and create market demand (customer value). In this case the introduction of variability in the system means, for instance, more variety in the product portfolio of a company. A basic idea behind fighting against vs. promoting variability in a system is rooted on how much return on investment over the long run a company is able to make (Hopp and Spearman 2000 p. 288).

"A particularly dramatic cause of variability is batching" (Hopp and Spearman 2000 p. 305). This enforces the need to address batching issues in a production system as a means of improving the system's performance and fighting against the undesired effects variability brings. In spite of the importance of this topic, batching issues do not seem to be of great concern in the AEC industry, although several researchers have begun to tackle the subject (e.g., Tommelein 1998, Chua and Shen 2001, Horman 2001, Arbulu et al. 2002). A remaining challenge is the development of appropriate metrics to evaluate the leanness of production systems in the AEC industry.

Batching is also important to scheduling, given that the choice of batch sizes influences cycle times, frequency of hand-offs, and thus the ability of a company to meet its due dates (Hopp and Spearman 2000). Appropriately sizing batches is fundamental to reducing work in progress and buffers in the system's interfaces, i.e., design-detailing-fabrication-installation. Small batch sizes allow for quick detection and correction of problems in production, and consequently allow for a smoother flow of work through the various workstations in a production system.

The creators of the Toyota Production System, Taichii Ohno and Shigeo Shingo, advocated that inventories should be reduced so as to reveal problems in production. Shingo (1988) goes as far as talking about "non-stock production" as an ideal to be pursued by companies, but he does not suggest that buffers should be absolutely removed eradicated. Likewise, Hopp and Spearman (2000 p. 226) stress that "zero inventory is not a realistic goal. Even under perfect deterministic conditions, zero inventory yields zero throughput and therefore zero revenue."

BUFFERS

Buffers in the form of physical parts, if not judiciously sized and located, may result in problems such as propagation of quality defects, unsteady flow of work, large amounts of capital tied up in inventory and work-in-process, reduction of the flexibility of a company to deal with rapidly changing demands, and so on (Hopp and Spearman 2000). Shingo (1988) developed one way to fight against the problems related to large physical inventories: the Single-Minute Exchange of Die (SMED). He conceived of change-over from one machine setup to the next being performed quickly, in single-digit minutes rather than hours, thereby making it more affordable to produce small amounts of different products instead of large batches of a single product. Through the continuous development of SMED techniques, Shingo reduced high set up times and large inventories.

AEC companies can benefit from SMED as well as other techniques developed by Toyota practitioners as a means of reducing the size of batches and buffers. However, as suggested by Howell and Ballard (1994), construction managers first have to acknowledge the uncertainty inherent to construction and control it, before buffers can be sized and located, and then progressively eliminate it. Arbulu et al. (2002) discuss batch sizes and their influence on lead times and production flows in AEC supply chains. They use simulation to show that large batches result in long lead times, whereas a one-piece-flow, or at least a small batch size, allows for a smooth flow of work with more frequent hand-offs and consequently smaller lead times. Other authors also have addressed issues related to location and sizing of batches (Tommelein 1998) and buffers (e.g., Howell et al. 1993, Tommelein 1999, Chua and Shen 2001, Horman 2001, Sakamoto et al. 2002) in construction.

DIFFERENT TYPES OF BUFFERS

To explain our analysis of buffers, first, we define the concept of production flows. According to Shingo (1988 p. 4), process and operations are two different phenomena of the structure of production and, as such, should be treated differently when one is analyzing production systems: "Process analysis examines the flow of material or product; operations analysis examines the work performed on products by worker and machine." Accordingly, buffers should also be differentiated and treated differently according to which axis, i.e., process or operation, they are located in. The rationale behind the differentiation of buffer types is that, depending on where people decide to locate buffers, they may be buffering the production either in the process- or in the operation flow.

Different types of buffers are needed to absorb different forms of variability (Schmenner 1993, Hopp and Spearman 2000). One can think about two main categories of buffers, namely passive and active (Table 1). Building on Shingo's (1988) work, passive buffers are related to the flow of the product/service, in Shingo's nomenclature the flow of process, i.e., materials, documents, semi-finished parts, and the like being worked on. A active buffers, i.e., operators, equipment, tools, are then located in the operations flow, where active resources interact with the goods in the process flow in order to transform, inspect, and transport these parts. In essence, these are the two general types of buffers that can be used to absorb variability in distinct phases, processes, and operations of a production system.

Table 1: Active vs. passive buffers

Type of Buffer	**Related to**	**Location**	**Examples**
Passive	Material, semi-finished parts, information, space, time, and money	Process flow, i.e. "flow of material in time and space" (Shingo 1988, p.4)	Raw material, i.e. sheet metal, kept on inventory to fabricate ducts. The material is kept in inventory to prevent a shortage of raw material and the need to stop production. Sketch drawings waiting to be processed by a CAD detailer. The detailer waits for a pile of sketches to accumulate so that he/she can group sketches to be input in the computer and nested by a software to optimize material usage.
Active	Operators, tools, equipment	Operation flow, i.e. "interaction and flow of equipment and operators in time and space" – transport, transformation, inspection - being performed through time (Shingo 1988)	Some machines are kept in the fabrication shop "just in case" they are needed to perform special types of products. Also, extra machines may be kept on the fabrication shop to deal with peak variations in demand. In the same fashion, a number of operators higher than necessary may be needed to cope with the same variations in demand.

Buffers were differentiated into two categories; the same is done for batches. Hopp and Spearman (2000) distinguish process batches from transfer batches. Process batches can be subdivided further in two types: serial batches, which are related to a number of parts of a same family that are processed in a workstation one after the other in a serial fashion; and parallel batches which refer to a group of parts that go through a workstation and are processed simultaneously. Transfer batches refer to the number of parts that are grouped together and sent from one workstation to the next as a group.

This paper next presents characteristics of the HVAC industry and the main impacts these have on design-detailing-fabrication-installation. Industry practices are analyzed in terms of batching and buffering issues and how these impact the overall performance of the system. The list of characteristics presented by the authors is far from complete, but it is based on the study of a variety of mechanical contractors and fabricators of HVAC duct work in the San Francisco Bay Area.

BATCHING AND BUFFERING PRACTICES IN THE DELIVERY OF SHEET METAL DUCTS AND FITTINGS

The authors' investigation of industry practices for producing sheet metal ducts/fittings and review of research by others as cited helped to identify various batches and buffers. This section characterizes batches and buffers and describes how work flows through different stages in the delivery of sheet metal ducts/fittings.

DESIGN

Miles and Ballard (2002 p. 85) claim that "[HVAC designs] are created under severe time constraints that result in drawings that are diagrammatic at best". Once the mechanical designer sends a set of drawings to the site, the site foremen have to check the actual status of the space in which the system will be placed. If necessary, they must change the size and other characteristics of the ducts/fittings before sending their drawings to fabrication. If information is missing, workers on site or in the fabrication shop may have to issue Requests For Information (RFIs) and then wait until these are answered before proceeding with their work. Therefore, the way design is carried out impacts the way ducts/fittings are batched for fabrication, as well as the way passive buffers accumulate, i.e., information or drawing for fittings wait to be processed in a single batch.

Based on the conversations we had with industry practitioners, fabricators and shop foremen communicate intensely with people on site to obtain clarifications, but they seldom communicate with designers. Only in cases where major changes in the project are needed will the Project Manager and the Site Foreman get in touch with designers. Some reasons for this communications divide are that the field and the office speak a 'different language,' they are concerned with different levels of detail, and, as suggested by Tsao et al. (2000), workers on construction sites may try their best to solve problems by themselves because they consider it to be their work to deal with problems and solve them with the resources and skills at hand; it is somehow part of the pride of their trade.

In the HVAC industry in the United States, the overall characteristics of ducts/fittings have been standardized by trade associations (e.g., SMACNA 1998), and they are further restricted by local government regulations, supply chain availability, and trade and company practices. For example, while ducts/fittings theoretically could have a height and width of any dimension, SMACNA has catalogued them according to discrete sizes using 1/2" and 1" (12.7 and 25.4 mm) increments, and building inspectors may demand the use of a specific type of connector. However, the actual lengths and angles of ducts/fittings, and the thickness of the sheet metal vary depending on the requirements of each project, thereby making the fabrication of ducts/fittings largely a make-to-order production process. Further study will explore the opportunity to streamline the design process and the flow of information and, consequently, the flow of production by reducing the number of different types of fittings and ducts. This includes developing metrics to assess local improvements (e.g., to evaluate how much better the shop might perform if parts were standardized) and systemic improvements (e.g., to trade off how the design process vs. HVAC system performance during building operation might be affected by the use of more standardized parts).

DESIGN-FABRICATION INTERFACE

Designers use CAD software for designing the HVAC system, but this software does not necessarily exchange data electronically with the software used to do the nesting and run the plasma cutters. When designers hand off paper drawings, design detailers have to manually input the data to generate the cut sheets for individual ducts/fittings.

FABRICATION

Orders for multiple ducts/fittings received from the site foreman may or may not be sent to fabrication in the same batch. The detailer and the shop superintendent control the sequencing of orders for different projects and manage how to best use shop capacity to meet the demand. The fabrication schedule takes into account factors such as the characteristics of the ducts/fittings and thus demand put on certain equipment and need for sheet metal of a certain type and gauge, the actual time when parts are needed on site, criticality of each project, who is working in the shop, and how busy the shop is on any given day. Features such as the need for insulation, the type of connection, the need to wrap each duct/fitting to keep it clean, and the type of material being processed determine duct/fitting lead times. Moreover, they also influence the way duct/fitting cutsheets are separated in different batches to take advantage of similarity of operations needed while minimizing setup times. Orders released to fabrication start at the plasma cutting table. Cutting is the operation that 'generates' all jobs. Batching at this stage is governed by the size(s) of the available sheet metal in addition to the nesting algorithms used.

Sheet-metal shop production rates usually are measured in pounds mass of sheet metal processed per week or month, and not in labor- or machine-hours per duct/fitting. Fabricators allege that due to the high variety of products they have to turn out, it is too tedious to collect data about productivity rates on the basis of individual ducts/fittings. However, software and hardware tools for tracking exist, such as bar coding systems that can track ducts/fittings and their parts in the fabrication shop. Operators can use these tools to log in the time spent on each machine and thus to compute the total number of labor hours and in-process time to fabricate ducts/fittings. Use of these tools would give more visibility to managers and help shops to gather data to support strategic decisions and trigger improvements in production. In fact, sheet metal shops that are more job-shop oriented, rather production oriented to support field operations, are more amenable to track at a greater level of detail. One of the companies visited uses a bar coding system to track the total time spent to fabricate each metal part. This company prices their orders in terms of labor-hours spent to fabricate a job instead of in pound mass of sheet metal. We speculate that this distinction in tracking stems from management treating their shop as a profit center instead of a cost center.

The synchronization of fabrication with installation is an important concern for mechanical contractors (Bhattal 2002). Parts have to be produced close to their installation time and failure to do so can result in excessive demand for storage space or production of parts that are not suitable for a specific project. Constantly, detailers have to communicate changes to the shop to avoid the fabrication of parts that are not adequate to the project. This problem deserves particular attention because parts that do not fit a project cannot (easily) be used in another project.

The more flexible types of parts in terms of use are frequently kept in inventory by fabricators, i.e., third-party suppliers to mechanical contractors, alongside high turn-around parts. The inventory of these parts, which constitute a passive buffer, helps fabrication shops to keep their lead times down. Some fabrication shops owned by mechanical contractors can turn out parts in a matter of a few minutes (e.g., ducts produced on a coil line) up to or a few hours (e.g., fittings and special parts). They have a combination of passive and active buffers. The capacity to quickly fulfill a project site's needs pays off, some companies may say, due to the high costs related to installation delays and due to the costs of idle workers on the job site.

FABRICATION-INSTALLATION INTERFACE

Mechanical, electrical, plumbing, and fire sprinkler trades are expected to constantly communicate and coordinate their efforts since their systems are distributed in the ceiling space and may interfere with each other. These trades compete with framers and dry wall installers for being the first to install their respective systems. 'The first one in wins' in that their work is unobstructed by that of other trades, but this of course may penalize trades scheduled to perform at a later time. This notwithstanding, despite the best coordination among trades, sometimes changes have to be made at the last minute before parts get fabricated so as to accommodate variations in routes and sizes of duct due to variations in field dimensions or unforeseen obstruction by systems already installed in the designated area.

New work preservation rules also are impacting mechanical contracting practices . In the San Francisco Bay Area, for instance, all HVAC duct work installed in the Union Local 104 area has to be produced in the Local 104 area. Capacity in fabrication shops that are located in other union jurisdictions—whether or not belonging to the company that installs the HVAC system in the Local 104 area—cannot be used to meet the demands of projects in the Local 104 area. The same challenge applies to fabricators because installers on projects in the Local 104 area will order from them only if their shop lies within the Local 104 jurisdiction.

BATCH AND BUFFER ALLOCATION THROUGHOUT THE HVAC PRODUCTION SYSTEM

The process represented in Figure 1 reveals the way batches and buffers are defined and distributed throughout the production system:

- From the site foreman to the fabrication shop: the transfer batch size equals the number of ducts/fittings needed on site based on how the site foreman organizes the crew's work. The foreman details and then faxes all the ducts/fittings needed for a so-called order. Since ducts/fittings are detailed by the foreman in a serial fashion, each of detailed drawing has to wait until the last one needed is finished so that the entire batch can be faxed to the fabrication shop.

- In the shop detailer's office: a stack of orders can accumulate in the detailer's office since foremen on different projects will send in their orders and there is so much a detailer can input per day. Besides inputting the data in the computer, the detailer will verify the detailed drawings and resolve ambiguities or missing data in characteristics of fittings, possibly by calling field personnel to get clarifications regarding the drawings. The pile of orders waiting to be processed at this stage can be considered a passive buffer located in the materials flow.

- Nesting: the shop detailer sorts out orders by project, inputs the data about each fitting in the computer, and then selects fittings to be considered in the nesting operation. The software optimizes the cutting process (minimal waste of metal sheets and efficient movement of the cutting head) but no consideration is made regarding the optimum use of the shop labor or other equipment.
- Cutting table loading and unloading: after each metal sheet is cut, the operator will move parts from the cutting table onto pallets. In this particular case, the transfer batch and the process batch are the same. Parts can be removed from the cutting table only when all the cutting for a single sheet is finished, because the sheet might get misaligned otherwise. Transfer batches and process batches do not have to be the same but in this case they are due to this equipment constraint. If there is a need for more throughput, it is important to have a cutting table with two loading tables so that while the machine is cutting a sheet on one side, the operator can unload the ready parts on the other side and then load the next sheet to be cut.
- Pallets: the parts for a fitting may or may not end up on the same pallet. Parts on a pallet will be fabricated in a serial fashion but, for example, ‘male’ and ‘female’ parts require the use of different equipment so they may be sorted accordingly. Pallets are stored on stacks or on the floor, thus serving as a passive buffer or work in process waiting to be processed. Operators that are cross-trained (who can work on multiple machines in the shop) will move a pallet (or a table on wheels) to a piece of equipment and work on all the parts on it, one after the other, before moving on to the next equipment. If operators are dedicated to working on a single machine, the pallet may be pushed from one equipment station to the next. In either case, while one part is being worked on, all the others have to wait, thus increasing the cycle time for producing a single fitting.
- Knocking together: when the component parts of various fittings have been fabricated, the pallet-based batches are broken up. The parts are spread out and matched up so that individual fittings can be knocked together.
- Sorting out: in the shipping area, a worker groups all the fittings that belong to the same order. If all the order’s fittings are finished and they fit in a truck, they are sent to the site in one batch. In this case, the transfer batch is equal to the process batch, if we consider the order the detailer sent at the beginning of the process to the fabrication shop. Therefore, the cycle time to turn out a fitting is relatively long since a finished fitting has to wait until all the other fittings for the same order are finished and sorted for shipment to the site.
- Site installation: fittings delivered to the site are moved to the location where they will be installed. Buffers at this point are not supposed to be large due to the

space constraints associated with site storage of voluminous fittings. These buffers of materials waiting to be installed will be depleted in a serial fashion if parts are installed one by one. Alternatively, they may be assembled as larger 'runs' on the floor and lifted to their final position as a group (Miles 2000).

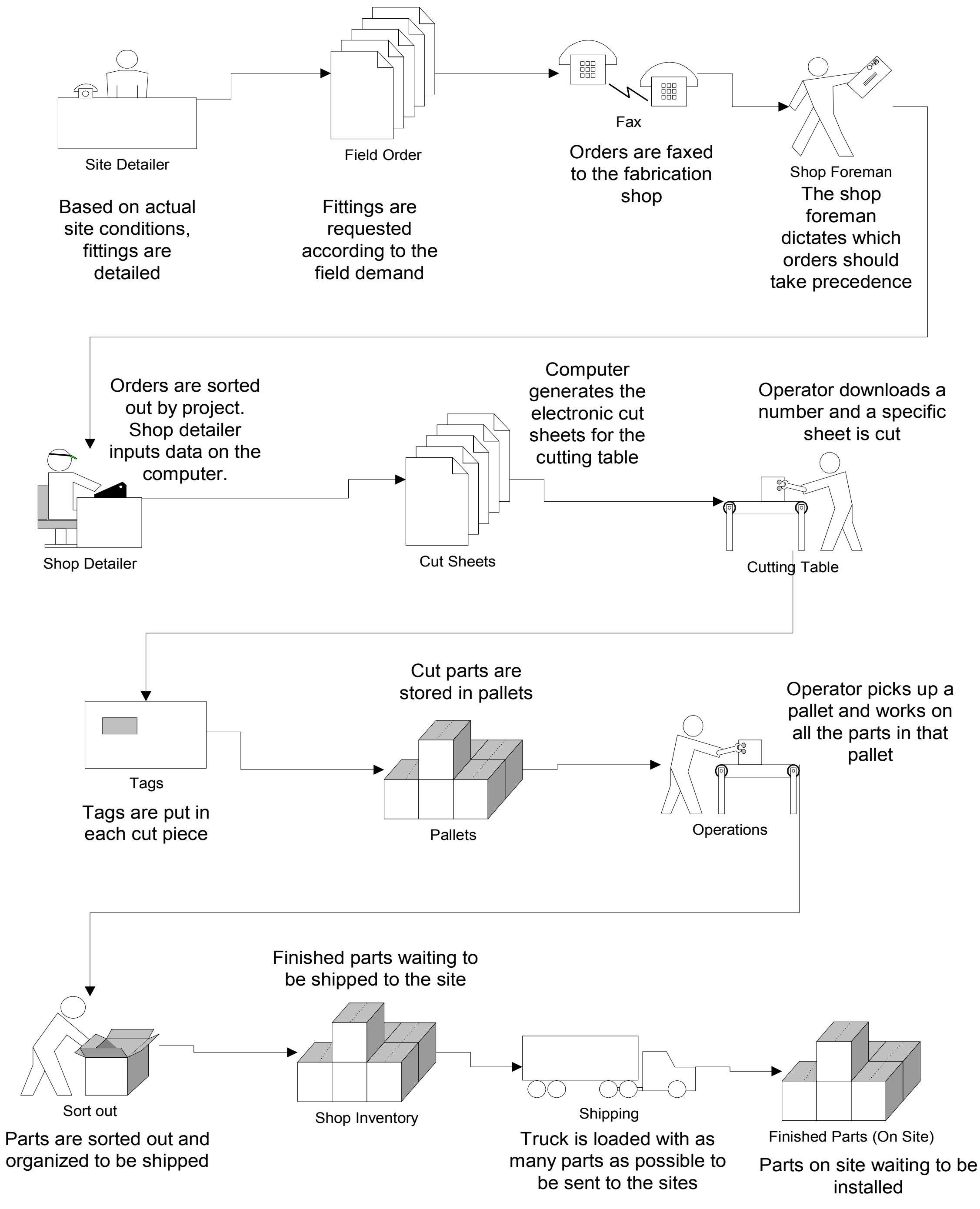

Figure 1: Process flow for fittings fabrication

THOUGHTS ABOUT THE HVAC INDUSTRY ORGANIZATION

Rules for batching and buffering exist in the fabrication process of HVAC ducts/fittings, but they largely remain tacit. The lack of widely disseminated knowledge of these rules, the fact that they are not clearly articulated, failure to decide where batching and buffering should occur, and lack of knowledge about types of buffers and batches and their influence on the system may result in inefficiency in this production system.

Mechanical contractors cannot afford to have crews idle on site due to the costs associated with productivity loss, contract agreements, and penalties for late work. In the case where a mechanical contractor has a fabrication shop, project managers may have more influence and perhaps confidence in how fast and reliably the shop can turn out parts and they will thus plan their orders and deliveries accordingly. But in the case where the production of ducts/fittings has to be outsourced to a third-party fabricator, managers may loose some of their control over the fabrication process, thus having to order parts longer in advance. Companies that buy from fabricators may still establish their own shop, perhaps with limited capabilities, if only to turn out parts quickly and to fabricate special types of fittings, i.e., "one-sies and two-sies" needed on an emergency basis. Idle workers on site may be prohibitively expensive as compared to keeping people in the fabrication shop on stand-by to deal with emergencies. Production shop capacity clearly serves as a large active buffer, including workers and equipment, with some very specialized equipment being used only on occasion. Reliability and on-time delivery are particularly important in this industry in part also because ducts/fittings are large parts that cannot be easily stored; therefore, buffers of finished parts are hard to keep.

Lead times for fabrication can be as little as a few minutes for ducts and a few hours for fittings. Process batches and transfer batches can be equal to one or as large as the number of parts needed. Shop detailers dictate in part the processing sequence of jobs and how many ducts/fittings and which ones are going to be part of a batch to be released for fabrication. Shop superintendents sequence the production and ultimately influence the way batches are handled.

The standards defined by SMACNA appear to be widely known and followed by sheet metal contractors and fabricators. SMACNA is an active and valued association, that may take on the challenge to help its member improve the HVAC supply chain. Improvements such as standardization of forms to order ducts/fittings from the fabrication shop and the further standardization of ducts/fittings are areas worthy of investigation. Finally, SMACNA together with sheet metal unions can play a major role in disseminating, in their publications and other training materials, concepts related to lean manufacturing (e.g., see Skinner (1999) for an initiative of disseminating lean concepts in the sheet metal industry).

In this paper, we discussed that different people in the sheet metal delivery process are consciously or unconsciously buffering the system, as well as sizing and sequencing batches based on tacit rules that may vary from project to project and shop to shop. In our visits to different fabrication shops, we also have been told that it is very hard to define the actual capacity of a shop due to the large number and types of ducts/fittings turned out by them. These topics, as pointed out by practitioners, represent opportunities for researchers to further investigate the HVAC industry's practices and define metrics to assess performance improvement.

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REFERENCES

Arbulu, R.J., Tommelein, I.D., Walsh, K.D., and Hershauer, J.C. (2002) "Contributors to Lead Time in Construction Supply Chains: Case of Pipe Supports Used in Power Plants." *Proc. 2002 Winter Simulation Conference,* E. Yucesan, C-H Chen, J.L. Snowdon, and J.M. Charnes, eds., 1745-1751

Ballard, G. and Howell, G. (1995) "Toward Construction JIT." *Proc. 1995 ARCOM Conference*, Association of Researchers in Construction Management, Sheffield, England.

Bhattal, N. (2002) *Process Simulation for Fabrication of HVAC Rectangular Ductwork Fittings.* Master of Engineering Report, Constr. Engrg. and Mgmt. Program, Civil and Envir. Engrg. Dept., Univ. of California, Berkeley, CA

Chua, D.H.K. and Shen, L.J. (2001) "Constraint Modeling and Buffer Management with Integrated Production Shceduler." *Proc. Ninth Annual Conference of the International Group for Lean Construction* (IGLC-9), 6-8 August, held in Singapore.

Holzemer, M., Tommelein, I.D., and Lin, S. (2000) "Material and Information Flows for HVAC Ductwork Fabrication and Site Installation." *Proc. Eighth Annual Conference of the International Group for Lean Construction* (IGLC-8), 17-19 July, held in Brighton, UK.

Hopp, W.J. and Spearman, M.L. (2000) *Factory Physics*. Second Edition. McGraw-Hill International Editions, Boston, 698 pp. (First Edition 1996)

Horman, M.J. (2001) "Modeling the Effects of Lean Capacity Strategies on Project Performance." *Proc. Ninth Annual Conference of the International Group for Lean Construction* (IGLC-9), 6-8 August, held in Singapore.

Howell, G. and Ballard, G. (1994) "Lean Production Theory: Moving beyond Can-Do." *Proc. Second Annual Conference of the International Group for Lean Construction* (IGLC-2), 28-30 September, held in Santiago de Chile, Chile.

Howell, G.A., Laufer, A., and Ballard, G. (1993) "Interaction between Sub-cycles: One Key to Improved Methods." *Journal of Construction Engineering and Management*, ASCE, 119 (4) 714-728

Miles, R.S. (2000) *Managing Workflow from Detailing to Installation*. 2nd Annual Lean Congress, Berkeley, CA, Lean Construction Institute, August 2000.

Miles, R.S., Ford, D.N., and Tommelein, I.D. (2002) "Modeling Considerations for Uncertain Supply of Mechanical Ductwork Systems." Draft paper.

Miles, R.S. and Ballard G. (2002) “Problems in the Interface Between Mechanical Design and Construction: a Research Proposal.” *J. of Construction Research*, 3 (1) 83-95, World Scientific Publishing Company.

Sakamoto, M., Horman, M.J., and Thomas, H.R. (2002) “A Study of the Relationship between Buffers and Performance in Construction.” *Proc. Tenth Annual Conference of the International Group for Lean Construction* (IGLC-10), 6-8 August, held in Gramado, Brazil.

Schmenner, R.W. (1993) *Production/Operations Management*. Englewood Cliffs, N.J.: Prentice Hall, 825 pp.

Shingo, S. (1988) *Non-Stock Production: the Shingo System for Continuous Improvement.* Cambridge, Mass.: Productivity Press. 454 pp.

Skinner, D. (1999). *Sheet Metal Made Lean and Clean: An Introduction to the Principles and Methods of Lean Production for Sheet Metal Shops.* Sheet Metal and Air Conditioning Contractors’ National Association, Inc., Chantilly, VA, 28 pp.

SMACNA (1998) *HVAC Duct Construction Standards*. Second Edition 1995 - with Addendum no.1 November 1997. Sheet Metal and Air Conditioning Contractors’ National Association, Inc., Chantilly, VA

Tommelein, I.D., Riley, D.R., and Howell, G.A. (1999) “Parade Game: Impact on Work Flow Variability on Trade Performance.” *Journal of Construction Engineering and Management*, ASCE, 125 (5) 304-310

Tommelein, I.D. (1998) “Pull-driven Scheduling for Pipe-spool Installation: Simulation of a Lean Construction Technique.” *Journal of Construction Engineering and Management*, ASCE, 124 (4) 279-288

Tsao, C.C.Y., Tommelein, I.D., Swanlund, E., and Howell, G.A. (2000).“Case Study for Work Structuring: Installation of Metal Door Frames.” *Proc. Eighth Annual Conference of the International Group for Lean Construction* (IGLC-8), 17-19 July, held in Brighton, UK.