MATERIALS AND INFORMATION FLOWS FOR HVAC DUCTWORK FABRICATION AND SITE INSTALLATION

Matt Holzemer,[1] Iris D. Tommelein,[2] and Shih-Lun (Aaron) Lin[3]

ABSTRACT

Designing and building heating, ventilation, and air-conditioning (HVAC) systems requires a set of complex activities and handoffs between multiple architecture-, engineering-, and construction practitioners. This paper highlights one part of the HVAC production network, namely the information and materials flow between fabrication shop workers and field installers.

The presented work aims to contribute to lean construction theory by describing current practices and strategies contractors use to cope with interacting sub-cycles and the upstream flexibility needed to accommodate downstream uncertainty. Accordingly, this paper explains what HVAC materials are handled and how. It then builds on qualitative data from several companies to illustrate two different production models used to fabricate and install HVAC components. One scenario describes how materials are "pushed" to the site. A second scenario describes how some materials are "pushed" and others "pulled." Scenarios vary because each contractor has to meet several project demands at the same time, because they have a specific business market niche and fabrication capabilities, different from competitors'.

The exploratory research described here paves the way for research into means to evaluate the effectiveness of different types of planning, the development of production system metrics to evaluate and promote better system-wide performance for fabricators and installers, and the implementation of heuristic- or optimisation tools for researchers to experiment with alternative production control scenarios in order to improve system-wide performance. Ultimately, our aim is to create explicit knowledge on how to increase the efficiency, reliability, and profitability of HVAC production systems.

KEY WORDS

Supply chain mapping, HVAC contractors, specialty contracting, push-driven scheduling, pull-driven scheduling, kanban, lean construction.

[1] Master of Science, Civil and Envir. Engrg. Department, 215 McLaughlin Hall, Univ. of California, Berkeley, CA 94720-1712, USA, 510/845-6486, FAX 810/592-8112, holge@uclink4.berkeley.edu

[2] Associate Professor, Civil and Envir. Engrg. Department, 215-A McLaughlin Hall, Univ. of California, Berkeley, CA 94720-1712, 510/643-8678, FAX 510/643-8919, tommelein@ce.berkeley.edu

[3] Master of Engineering, Civil and Envir. Engrg. Department, 215 McLaughlin Hall, Univ. of California, Berkeley, CA 94720-1712, USA, shihlunl@uclink4.berkeley.edu

INTRODUCTION

Designing and building heating, ventilation, and air-conditioning (HVAC) systems requires a set of complex activities and handoffs between multiple architecture-, engineering-, and construction (AEC) practitioners. To illustrate this, the present paper highlights one part of the HVAC production network, namely the interaction between fabrication shop workers and field installers.

The presented work aims to contribute to lean construction theory by describing current practices and strategies contractors use to cope with interacting sub-cycles and the upstream flexibility needed to accommodate downstream uncertainty. Characterizations of AEC systems in terms of their production processes have been sorely lacking in the literature. Initial research into ready-mix concrete (Tommelein and Li 1999) and structural steel process supply chains (Al-Sudairi et al. 1999, Tommelein and Weissenberger 1999) were reported at the IGLC conference last year. The goal of the present work is to describe how HVAC contractors coordinate tightly coupled, yet geographically distributed operations, namely ductwork fabrication and site installation.

The most widely used performance measures in construction focus on on-site productivity (Oglesby et al. 1989). These measures fail to consider the impacts of upstream activities on workflow or downstream performance (Howell and Ballard 1994, Tommelein et al. 1999). Such impacts can be significant in production systems subject to interdependence and uncertainty (Crichton 1966), and especially in those that comprise many different products because matching problems will be prevalent (Tommelein 1998). HVAC systems built by mechanical or sheet metal contractors are a prime example of this class of systems.

HVAC contractors hand off work internally when they fabricate and install their own ductwork, as is common industry practice. It therefore is in their best interest to make the handoff as efficient as possible. In theory that should be easy since the two functions coexist within the same company. In practice, competition arises as a natural consequence of tension between job-shop production in the fabrication shop and project-driven production at the various construction sites. The shop and the project sites often have different goals and performance incentives, so they may end up vying for control of the handoff.

As a first step towards understanding current practice, this paper begins to describe the operations that are performed in shops where HVAC ductwork is fabricated. It reviews the planning and communication processes that direct the fabrication shop to make duct segments and ship them to site. This paper provides a qualitative description of the processes. It generalizes observations made at several fabrication shops. Descriptions may therefore not correspond to any individual contractor’s practice. In subsequent research we will look at system performance metrics.

HVAC BACKGROUND

DUCTWORK

A combination of ductwork and equipment (e.g., air handling units) make up an HVAC system. HVAC ductwork is the focus of this paper. Ductwork can be decomposed into four basic types: rectangular duct, spiral duct, fittings, and components.

Straight HVAC runs are made using rectangular or spiral (round) duct. Rectangular duct (Figure 1) comes in standard sizes, metal wall gauge, and—where appropriate—

internal insulation thickness. Spiral duct (Figure 2) is also available in a standard number of weights and sizes, but it is not insulated. Both rectangular and spiral duct are made in specialized machines, using separate processes. HVAC duct fittings (Figure 3 and 4) are the complex shapes used to bend, neck down, break, and combine runs of ductwork. Fittings are mostly fabricated by hand in a long process involving many different machines. Components (Figure 5) are the special items that go into HVAC systems, such as fire dampers, grilles, coils, and fans. They are ordered from vendors to be combined with other pieces of ductwork in the shop or in the field.

Figure 1: Inventory of rectangular duct in fabrication shop

Figure 2: Inventory of round duct in fabrication shop

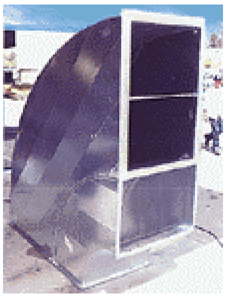

Figure 3: Rectangular duct fitting (www.omniduct.com/products/rectangular.html 6-28-00)

Figure 4: Tapered fitting connecting round to rectangular duct

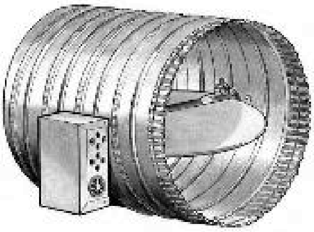

Figure 5: Round duct component with damper and actuator (from www.serv-air.com/catalog/young.html 6-28-00)

SHOP FABRICATION

Rectangular duct, spiral duct, and duct fittings are custom made by sheet metal workers off-site, in a protected shop. They are made to order so as to meet specific project requirements. Figure 6, depicts a typical shop floor layout and the fabrication process is described below. Segroves (1989) provides a sample shop layout along with guidelines for duct fabrication shop management. He describes tool capabilities and locations, but he does not illustrate material flows. Our aim here is to show how materials flow through the shop because flow affects process efficiency (SMACNA 2000). We discuss three materials flows, one for each type of duct. Material flows and actual operations performed at each machine will vary from shop to shop, depending on the skill of workers and machines available in each shop, and other projects' demands on shop capacity.

Rectangular duct begins as either rolled or flat sheet metal (the duct wall) that is bent, cut, and insulated using a machine called a "coil line". Each segment then moves to another workstation where workers prepare the flanges at either end to attach to other duct runs in the field. The seams are then made airtight and larger duct segments are internally braced by hand. The coil line can make duct of different lengths, but maximum dimensions are governed by the stock material, which usually is 4 ft (124 cm) wide. It only takes a few minutes to retool the coil line between sizes.

Spiral duct is fabricated from a roll of narrow (4-6 inches or 10-15 cm) sheet metal on a single machine that rolls the metal band into a round opening, and crimps it. The machine can make duct of any length. It is difficult to change over between different duct sizes and gauge because workers must mount each new roll of stock material exactly at a specific angle to match the required diameter of the duct being made. This changeover time affects the quantity of duct of a specific kind that will be batched (Figure 2).

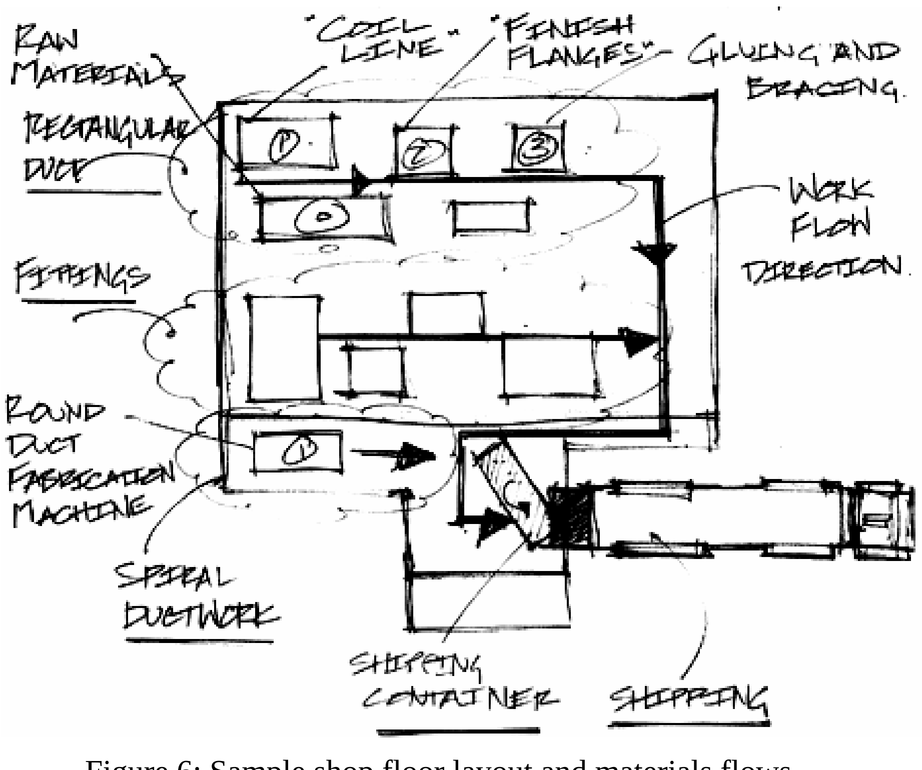

Figure 6: Sample shop floor layout and materials flows

Duct fittings are more difficult to fabricate due to their complex geometry. First, the fitting shape is "unfolded" using a computer program. Next, the program lays out shapes to make optimal use of the available stock material (stock cutting problem). Finally, it directs the plasma cutter or a laser device to cut the flat sheet metal. The use of computer-aided manufacturing technology (CAM) is commonplace in US sheet metal shops. Then, workers shape the cut metal, trim it further, fold it, finish its edges, apply insulation, and seal its seams using a variety of machines at different work stations.

HVAC VENDORS

Vendors broker lines of components or other engineered items that go into HVAC systems, such as fire dampers, grilles, coils, and fans. Many components are standardized so they can be mass-produced by manufacturers.

HVAC contractors procure materials by issuing purchase orders (POs) to vendors. Vendors respond with bids based on performance specifications or by providing brand name components when requested. In rare cases, HVAC subcontractors circumvent vendors by going directly to a manufacturer to place a very large order. Vendors create value in the supply chain by providing local contacts for manufacturers, distributing products, stocking, and breaking bulk.

RAW MATERIAL PROCUREMENT

The contractors we interviewed use different strategies to procure materials for fabrication vs. construction. In most cases the fabrication shop expects to produce a more-or-less steady amount of work each month. Some contractors own highly-specialized equipment and use it to make duct, not only to be installed by their own construction crews, but also to be supplied to competing contractors that may not be so efficient at making those, for them more unique pieces. Depending on the work the contractor considers to be their market niche, some shapes, sizes, and materials will be more commonly used than others. According to the requirements, the shop stocks raw materials with a minimum-maximum inventory control strategy. They reorder raw materials (like sheet metal) and indirect inventory (like earplugs) through one-time POs or long-term contracts. Using a PO, the shop tries to assure good pricing by competitively bidding work out. Using long term contracts, vendors form a relationship with the shop and even visit to help them manage their stock. Any cost differences are then likely to be offset by gains in procurement efficiency.

By contrast, construction groups use POs to procure HVAC components on a job-by-job basis. Alternatively, they may purchase large amounts of common materials to obtain a quantity discount, anticipating that remnants will be used on subsequent projects. Some companies have adopted a multi-project procurement strategy in order to obtain better pricing and supplier performance.

SHIPPING HVAC DUCT

The most straightforward way to handle HVAC duct is to move individual segments by hand. In order to expedite field installation, it is not uncommon for fabricators to pre-assemble several of them. The number of segments joined is constrained by the means available for shipping and handling, and hoisting the assembly into position at the work face. When hand loading is difficult, because duct segments are too big or too heavy, segments may be palletized and handled by forklift. HVAC duct typically is trucked from the fabrication shop to the construction sites. Shop helpers will carry individual pieces and place them in a truck container, or load pallets onto a flatbed. Handling means vary depending on whether the site is located nearby or hundreds of miles from the shop where fabrication takes place.

Figure 7 illustrates the delivery of materials brought to site in a truck with a trailer. Immediately upon arrival on site, the trailer is hoisted by a tower crane and then be off loaded at the work face. The empty trailer is returned to street level, reloaded with materials in the truck, and hoisted up a second time.

Figure 7: Hand loading of duct segments from delivery truck to trailer that doubles as container for hoisting by crane

Hoisting by crane is efficient but it assumes that the work face is accessible by crane. Fabrication and site delivery will in this case have to keep up with the pace at which construction progresses. When duct needs to be delivered to a location not accessible by crane, or when the crane is removed from the site (when it is no longer needed for structural frame erection and when it is not economical to have it support other construction operations), duct will be handled piece by piece and loaded into a man lift. This is a more labor intensive operation. Whether a crane or a man hoist is used, the flow of HVAC materials on site must be coordinated with other contractors that use the same access paths and hoisting means. Specialty contractors may bring in their own materials handling and hoisting means. This enables them to de-couple their logistics activities at least to some extent from that of others.

Fabricated HVAC materials may also be shipped in a container (Figure 8), which protects its contents from environmental impacts. This is particularly important, for instance, when the HVAC system is part of a high-tech facility. When duct is to supply air to a clean room in a wafer fabrication plant or biomedical facility, it too may have to be fabricated in a clean room environment. Each piece will then be shrink wrapped to keep dust out until installation.

Figure 8: Shipping container

The entire container may be hoisted to the floor level where materials are needed. To allow for container access, the installation of exterior wall panels, windows, or perhaps even a structural component may have to be delayed. Loading and unloading may be assisted using a mobile dolly that rolls in and out of the container. The added cost for containerizing and using a bigger hoist for handling is recuperated by improving protection and handling efficiency.

Vendors typically assume responsibility for shipping components. When they ship materials directly to the field—which is the best scenario—they will call ahead to check if the shipment should proceed as planned. It not, the shipment may be diverted to a rigging yard to delay it until the site is ready.

COORDINATION OF INFORMATION AND MATERIAL FLOW

SCENARIO 1: PUSH FLOW

Scenario 1 describes how a medium sized HVAC contractor uses a master schedule for field installation to "push" duct through the shop to the construction site. The process is depicted in Figure 9.

The architect or mechanical engineer hand off construction drawings to the mechanical contractor's draftsman. These drawings show runs of ducts and flow rates but do not necessarily specify dimensions or shapes of duct segments. The contractor then creates a set of very detailed shop drawings that describe exactly what will be fabricated and in what pieces.

The shop drawings form the basis for a material quantity take off (QTO), summarized in a bill of materials (BOM), that reflects how much of what materials are needed to fabricate the duct (though not necessarily what is needed for field installation). Since long lead items by definition take a lot of time to procure, they typically are ordered separately before the architect and/or owner approves the shop drawings. The mechanical contractor may or may not have purchasing responsibility for long lead items. Regardless of the situation, if design changes are made after long lead items have been ordered, the contractor's production and installation plans are likely to be impacted.

In a competitive-bid situation, after contract award, the general contractor (GC) typically holds a private planning meeting (sometimes called a "pre-construction meeting") with the HVAC contractor to set a construction schedule that meets their own and the HVAC contractor's goals. The construction schedule is updated during the project, and continues to serve as a guide for the shop and procurement departments. This schedule sets the pace for on-site installation and thus for fabrication.

The BOM in concert with the construction schedule is used to order materials for the project, which must be delivered by their vendor when needed for installation. When non-stock materials are needed, the BOM is also used to purchase raw materials for the fabrication of rectangular duct, spiral duct, and fittings.

As soon as the shop drawings for HVAC fittings are completed, they are turned into Computer Aided Machining (CAM) instructions that drive the sheet metal cutting devices used to produce fittings. The fittings are matched to areas corresponding to work on the construction schedule, and then fabricated in time to be delivered to the site. Likewise, runs of straight and spiral duct are coordinated with the construction schedule.

When the rectangular duct, spiral duct, fittings, and components are all received at the work face where work has been planned to proceed, and everything on site is ready, the work can begin.

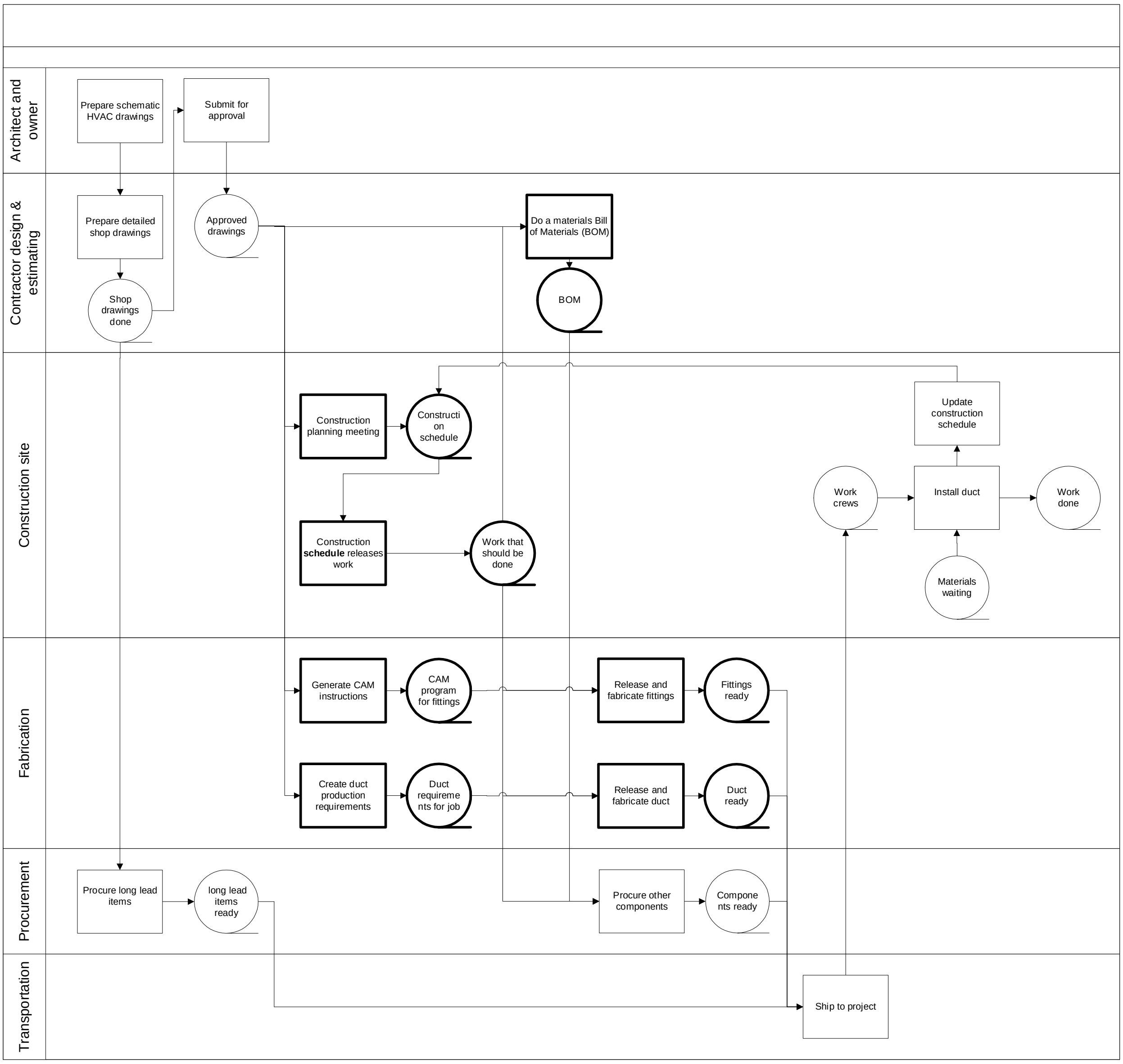

Figure 9: Push flow of materials

SCENARIO 2: PUSH AND PULL FLOW

The second scenario describes how larger HVAC contractors my trigger fabrication as needed in response to pull messages from the construction site, while pushing long lead items with a construction schedule. The process is depicted in Figure 10. The differences with scenario 1 are marked with bolded rectangles and circles.

The shop drawings and the construction schedule are produced in a similar fashion as they are in scenario 1. Long lead items are also procured in a similar fashion. However, a difference with scenario 1 is that, as work progresses, the field supervisor prepares and places specific orders for ductwork and HVAC components. The field supervisor develops QTOs in the field and describes duct configurations on “spool sheets”. Spool sheets are drawings with templates that depict various duct shapes on which critical dimensions are to be filled out. The individual who orders materials must know how long it will take to get each of the items they need, so they can put their order in on time. Shop order lead times (the time between submission of a spool sheet and the delivery of the fabricated piece on site) appears in practice to vary from a few days to a week or so. This variation is a function of the complexity of the piece, the shop capacity and work load, as well as the availability of transportation. Upon receiving requests from the field, the fabrication shop enters data into a computer model, which develops CAM instructions used by the cutting devices. Fabrication continues much as described above and the materials are shipped out.

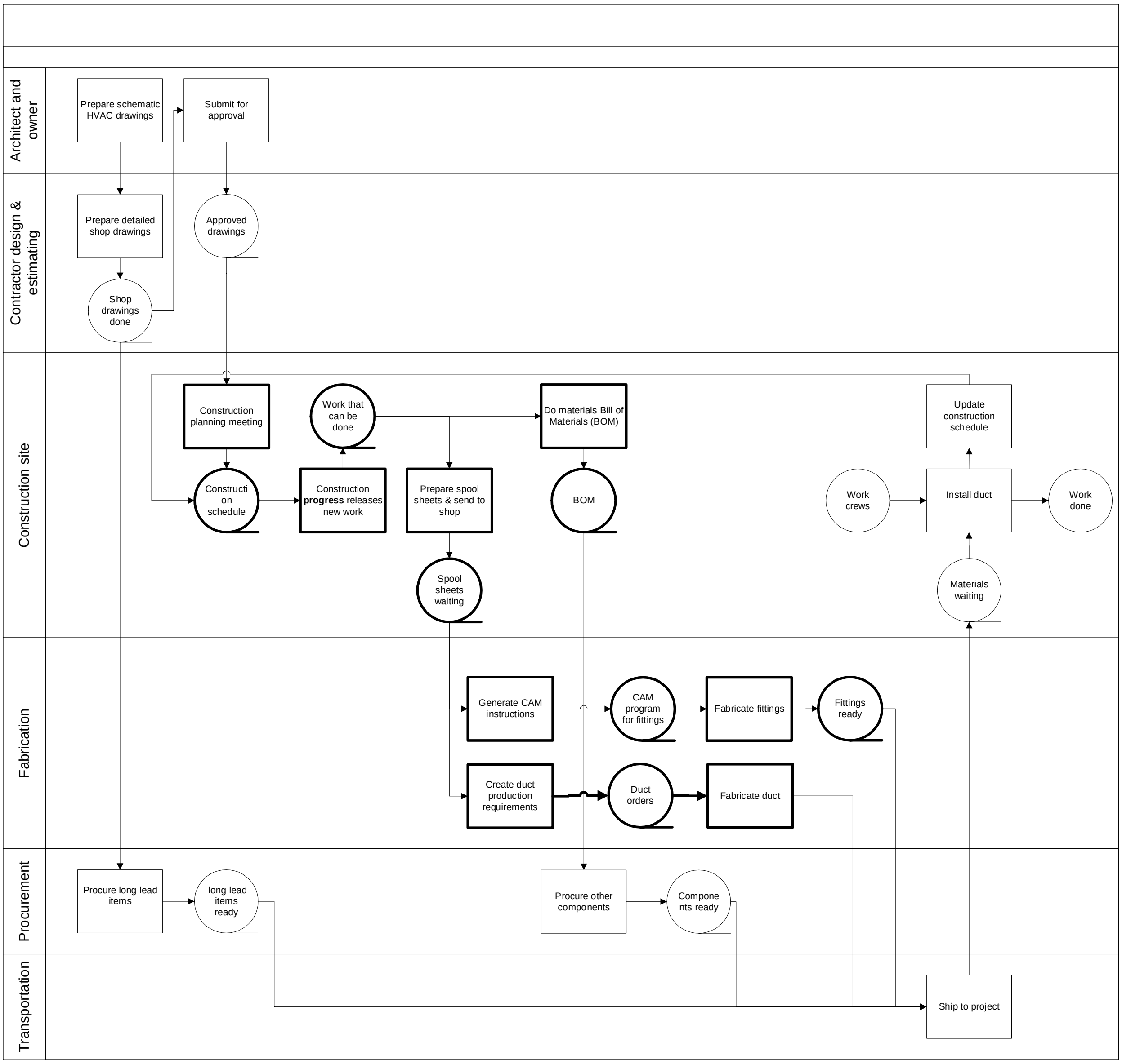

Figure 10: Push and pull flow of materials

DISCUSSION

PUSH VS. PULL

The two material-flow scenarios use different production control mechanisms. They push or pull materials through the system. Tommelein (1998) defines the differences. In a push-driven system, "It is assumed that all resources required to perform an activity that is about to start will indeed be available at that activity's early-start time… each activity passively waits for its ingredients (instructions, labor, materials, equipment, and space) to become available... When some have become available but others needed at the same time have not, those available will wait in a queue or buffer for the combination of resources—the set of "matching parts"—in its entirety to be ready. While it may be possible to start work with an incomplete set of resources, chances are this will negatively affect productivity … rigorously adhering to the initial schedule may not be the best approach for successful project completion as network characteristics and resource availability will deviate from those assumed when that schedule was generated."

In a pull-driven system, "resources must be selectively drawn from queues—so the activity that processes them will be busy just the same—but chosen so that the activity's output is a product needed further downstream in the process, and needed more so than its output using other resources in the queue would have been. Resources' wait time in queues should be minimized."

Our description of the use of push vs. pull in practice has been schematic. We need to obtain more specific information in order to better explain why some contractors use spool sheets to pull HVAC duct to site whereas others do not. Nevertheless, using a pull-driven approach has many advantages, especially in situations where uncertainty prevails. Uncertainty may pertain to system complexity (e.g., how many parts must match up for work to be executable?), design changes, dimensional tolerances, interference of the detailed HVAC system design with other detailed system designs that were developed concurrently, sequencing of work, access to the work face, material deliveries, etc. The push driven model is appropriate when project conditions are more certain. This is consistent with what we learned from the contractors we interviewed. At a first glance, those who use the push-pull model work on larger and more complex projects than those who use the push model. Additional data must be collected to substantiate this further.

As for the long lead items, they appear to be pushed in both scenarios, although it is possible that some pull mechanism using a longer-term lookahead system is at play (Tommelein and Ballard 1997). This too requires further investigation.

This research did not quantify which of the two methods for coordinating the flow of materials is best. Each has value depending on the contractor's market niche and operational requirements. Many production systems have grown 'organically' over time. They may in fact be quite close to optimal. But it is unlikely that they are sufficiently agile so as to adapt to individual project needs. Our aim in detailing production systems is to reveal their intricacies and complexity, and then learn to purposefully tailor them to best meet individual company and projects' needs.

WORK STRUCTURING

As mentioned, fabricators may pre-assemble several duct segments once they have been fabricated in the shop, prior to shipping. We have visited shops where three of four rectangular duct segments, each of the same dimensions, were combined into one. This raises the question as to why the duct had been segmented into smaller pieces to start with. We speculate that it is because of the limited width of stock materials, and constraints on machining and tooling. In addition, contractors who do not know in advance what the access constraints will be at the work face, must make conservative assumptions early on (Gil et al. 2000), that is, make smaller pieces. When site access constraints become known, contractors may be able to relax these assumptions, that is, make bigger pieces. If at that time, fabrication of smaller pieces is already underway, then bigger pieces will have to be assembled using those smaller ones as is the case in the situation we observed. A ‘work structuring’ (Ballard 1999, Tsao et al. 2000) effort is in order to analyze and improve this production process.

SUMMARY

This paper has introduced the basic HVAC duct work materials and outlined how they are fabricated and shipped to construction sites. It has described how on-site construction is co-ordinated with off-site fabrication in the HVAC production network. Data from several companies was used to characterise two different scenarios for procuring, fabricating, and shipping HVAC components. One scenario described how materials are pushed through fabrication to the site using a master schedule, which is kept up to date by field crews. A second scenario described a combination of push and pull: long lead items and ductwork components are pushed to the site based on a master schedule, whereas ductwork is fabricated according to spool sheets that convey pull from the construction site, so the right ductwork is fabricated shortly before the field foreman needs it. Scenarios vary because individual contractors have to meet specific project demands, while they have their own business market niche and fabrication capabilities, different from competitors’.

The exploratory research described in this paper paves the way for research into (1) means to evaluate the effectiveness of different types of planning and co-ordination; (2) development of production system metrics to evaluate and promote better system-wide performance for installers and fabricators; (3) implementation of heuristic- or optimisation tools for researchers to experiment with alternative production control scenarios in order to improve system-wide performance. Ultimately, our aim is to create explicit knowledge on how to increase the efficiency, reliability, and profitability of HVAC production systems.

ACKNOWLEDGEMENTS

We are grateful for all assistance provided by the people we interviewed, for the time they spent and the knowledge they shared with us regarding their fabrication shop and construction site operations. This research was supported in part by discretionary funds provided by the Specialty Construction Institute and the Construction Employers Association, whose support is much appreciated. Any opinions expressed in this paper are the authors’ and do not necessarily reflect those of the people interviewed or of the organizations that provided discretionary funding.

REFERENCES

Alarcon, L. (ed.)(1997). *Lean Construction*. A.A. Balkema, Rotterdam, The Netherlands, 497 pp.

Al-Sudairi, A.A., Diekmann, J.E., Songer, A.D., and Brown, H.M. (1999). “Simulation of Construction Processes: Traditional Practices Versus Lean Principles.” *Proc. Seventh Ann. Conf. Intl. Group for Lean Constr.*, IGLC-7, 26-28 July, held at U.C. Berkeley, CA, 97-108. Available at http://www.ce.berkeley.edu/~tommelein/IGLC-7.

Ballard, G. (1999). “Work Structuring.” *White Paper 5* (unpublished), Lean Construction Institute, Ketchum, ID, http://www.leanconstruction.org/

Crichton, C. (1966). *Interdependence and Uncertainty, A Study of the Building Industry*. Tavistock Publications Limited, UK.

Gil, N., Tommelein, I. D., Kirkendall, R.L., and Ballard, G. (2000). “Contribution of Specialty Contractor Knowledge to Early Design.” *Proc. Eighth Annual Conference of the International Group for Lean Construction* (IGLC-8), 17-19 July, Brighton, U.K.

Howell, G. and Ballard, G. (1994). “Implementing Lean Construction: Reducing Inflow Variation.” *Proc. 2nd Ann. Meeting of the Intl. Group for Lean Construction*, Pontificia Universidad Catolica de Chile, Santiago, September, reprinted in Alarcon (1997) 93-100.

Howell, G.A., Laufer, A., and Ballard, H.G. (1993). “Interaction Between Sub-Cycles: One Key to Improved Methods.” ASCE, *J. Constr. Engr. and Mgmt.* 119 (4) 714-728.

Koskela, L. (1992). “Application of the New Production Philosophy to Construction.” *Tech. Report 72*, CIFE, Stanford Univ., CA, September, 78 pp.

Oglesby, C.H., Parker, H.W., and Howell, G.A. (1989). *Productivity Improvement in Construction.* McGraw-Hill, Boston, Mass. 588 pp.

Segroves, J.L. (1989). *Shop Layout: A Guideline to Duct Shop Management*. SMACNA Business Management Education Committee, reprinted in 1997, 75 pp.

Skinner, D. (1999). *Sheet Metal Made Lean and Clean: An Intro. to the Principles and Methods of Lean Production for Sheet Metal Shops*. SMACNA, Chantilly, VA, 28 pp.

SMACNA (2000). “Revised Shop Layout Pays off Handsomely.” *Industrial Insights*, SMACNA Industrial Contractors Council, June, 4 (1) 4.

Tommelein, I.D. (1998). “Pull Driven Scheduling of Pipe Spool Installation: Simulation of Lean Construction Technique.” ASCE, *J. Constr. Engr. and Mgmt.* 124 (4) 279-288.

Tommelein, I.D. and Ballard, G. (1997). “Lookahead Planning: Screening and Pulling.” *Proc. Second Intl. Seminar on Lean Constr.*, 20-21 Oct., organ. by A.S.I. Conte. Logical Systems, Sao Paulo, Brazil.

Tommelein, I.D. and Li, A.E.Y. (1999). “Just-in-Time Concrete Delivery: Mapping Alternatives for Vertical Supply Chain Integration.” *Proc. Seventh Ann. Conf. Intl. Group for Lean Constr.*, IGLC-7, 26-28 July, held at U.C. Berkeley, CA, 97-108. Available at http://www.ce.berkeley.edu/~tommelein/IGLC-7.

Tommelein, I.D. and Weissenberger, M. (1999) “More Just-in-Time: Location of Buffers in Structural Steel Supply and Construction Processes.” *Proc. Seventh Ann. Conf. Intl. Group for Lean Constr.*, IGLC-7, 26-28 July, held at U.C. Berkeley, CA, 109-120. Available at http://www.ce.berkeley.edu/~tommelein/IGLC-7.

Tommelein, I.D,. Riley, D., and Howell, G.A. (1999). “Parade Game: Impact of Work Flow Variability on Trade Performance.” ASCE, *J. Constr. Engrg. Mgmt.*, 125 (5), 304-310.

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 Ann. Conf. Intl. Group for Lean Constr.* (IGLC-8), 17-19 July, Brighton, U.K.