PROCESS BENEFITS FROM USE OF STANDARD PRODUCTS – SIMULATION EXPERIMENTS USING THE PIPE SPOOL MODEL

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ABSTRACT

Construction materials management and supply chain management are challenging not in the least because of the sheer number and variety of types of materials being assembled in any one project. Uniqueness of materials increases system complexity. This raises the question addressed in this paper: How may the use of increasing numbers of a standard product affect production system performance? To answer this question, we build on the pipe-spool model with 'matching problems' that was presented at the IGLC in 1997 but we study parameters that are different from those studied previously to illustrate how management practices may affect a production system's behavior. Specifically, we show how the use of standard products alleviates the matching problem.

Computer-based discrete-event simulation is known to be a useful tool to describe how lean systems may be designed and metrics applied to analyze their performance. Accordingly, we use simulation experiments to illustrate the relationship between the use of various numbers of standard products and process execution. As shown, small numbers of standard products result in some reduction of the project duration, but increasing numbers benefit the system disproportionately more. Using lessons learned from this experiment combined with other observations based on theory and practice, we provide directions for follow-on research and recommendations for managers to design their project-based production systems by exploiting product standardization opportunities.

KEY WORDS

Lean construction, variability, product standardization, process modelling, materials management, supply chain management, discrete-event simulation, pipe, piping system, process plant, industrial construction, off-site fabrication.

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INTRODUCTION

System Complexity Due to Uniqueness of Materials

Construction involves installing materials in a facility being built. Prerequisite to starting field work in a specific work area is to make sure that materials are on hand as needed to complete each work assignment. If materials are missing, the assignment is not sound (Ballard and Howell 1998) and should be deferred, even though the temptation may be great to go ahead and make-do (Koskela 2004).

Construction materials management (CII 1988) and supply chain management (Tommelein et al. 2003) are challenging not only because of the number of people involved in deciding what materials to specify for any one project and how to supply them, combined with uncertainty regarding the timing of the need for materials, but also because of the sheer number and variety of types of materials being assembled. Many construction materials are *allowed* to be unique. There is a tendency in the industry for engineers to want to engineer and, by extension, for 'architects to want to architect' (Gero 1987). Designers may think that sharpening their pencil to create unique solutions is their contribution to delivering value to the product the customer ultimately wants, but customers do not necessarily appreciate such efforts. The uniqueness of a facility as a whole may well be of value to a facility owner, users, and other stakeholders, however, it is questionable as to whether the uniqueness of parts of that facility (such as doors and windows of various dimensions, supports and fixtures of different types, left- and right-handed mechanical equipment that will get hidden in the plenum space, etc.) necessarily contributes to overall value. In any case, such uniqueness of materials increases system complexity and thus makes it more challenging to manage the production system.

Matching Problem Terminology

The terminology in this paper is not commonly used, so definitions are in order. A 'specific' material, here, refers to a material that is one-of-a-kind (unique) in the context of a facility being built; that is, the facility's design includes only one instance of it. Consequently, there is only one location in the facility where it should end up in the process of construction. Field crews must make sure that each specific material and its designated location exactly 'match' before proceeding with installation. Mismatches due to delay and uncertainty in supplying materials or completing prerequisite work at those locations hamper field productivity. In contrast, 'standard' material, here, refers to a material of which identical multiples (recurring) are used in a facility.

We claim that the use of larger numbers of standard materials replacing specific materials in a facility creates flexibility in the production system, that is, it alleviates the matching problem. Intuitively, indeed, availability of standard materials creates the opportunity to use any one in any one of several locations in the facility being built.

Research Methodology

To sharpen intuitive support of this claim, we developed a computer-based discrete-event simulation model to describe a system with a matching problem. We then conducted simulation experiments to illustrate the relationship between the use of various numbers of standard products and the duration of process execution.

PIPE-SPOOL SIMULATION

Pipe Spools in Design, Fabrication, Shipment, and Installation

Industrial facilities such as oil refineries or other process plants comprise foundation systems, structural systems, and numerous units of electro-mechanical equipment and vessels to process and store the products of interest. Equipment and vessels are connected by means of pipe for product to flow through. Control systems incorporating valves, instrumentation, and electrical components complete the integrated system.

Piping system designs (typically depicted using isometric drawings) include pipe sections of various materials and dimensional properties (diameter, wall thickness, length, etc.), transition pieces, in-line instrumentation, and supports. These components are connected using welds or bolted flanges, they are supported underneath or suspended by means of hangers from the structure, and they crisscross in seemingly all directions to achieve the desired plant functionality. Because of the complexity of work involved in building piping systems and the challenging work environment so characteristic of construction, sections of the system called pipe spools (typically depicted using cutsheets) (Figure 1) get fabricated off site and are then shipped to site for final assembly. Some practitioners claim that fabrication off site can be on the order of three times more productive than fabrication on site. How to break a piping system into spools (the spooling process) is decided based on rules and heuristics. For example, a factor limiting the length of spools is the length of the flatbeds used to transport them, often 40 feet or about 12 meter (Figure 2).

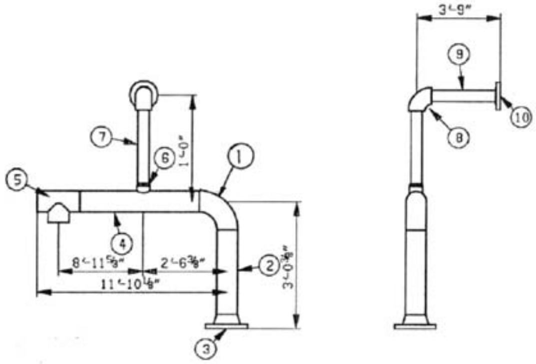

Figure 1: Excerpt from a Cutsheet of a Specific Pipe Spool (note disproportionate scaling)

Figure 2: Staging of Pipe Spools (© 1995 Iris D. Tommelein. All Rights Reserved.)

The process for constructing an industrial facility is incredibly complex as it involves installing many hundreds if not thousands of unique pipe spools, not to mention all other components. The Business Roundtable (BRT 1982) identified the piping process as being critical to the success of numerous industrial projects. Not surprisingly, a significant number of research studies have been conducted on the subject of industrial piping systems with product and process improvement in mind (e.g., CII 1996, Howell and Ballard 1996, O'Connor and Liao 1996, O'Connor and Goucha 1996).

Previous Work on the Pipe-spool Model

The 'matching' problem was described and illustrated using the Pipe-spool Model, a model of a supply chain that is typical of fast-track process-plant projects (Tommelein 1997a, 1997b, 1997c, 1998, 1999). The Pipe-spool Model simulates the flow of 600 specific pipe spools, designed and fabricated off-site, each one designated for installation in one specific area among 15 areas (totaling 40 spools per area) of a facility under construction. The model shows design and fabrication taking place off site, and spools being shipped to the site, while construction progresses on site. Off-site and on-site work paths of activities merge when it comes to installation.

The flow of pipe spools in this model is stochastic, which means that the order and timing of specific spools going through specific steps of the process is subject to variability, and the manifestation of this variability is governed by randomness. Various kinds of variability were modeled: (1) variability pertaining to the duration for completing process steps, (2) variability in sequencing work, (3) variability caused by execution quality (defects) in process steps, thus necessitating variability in routing when rework is needed, and (4) variability in timing caused by batching. Such variability leads to merge bias, resulting from merging sequences of activities (e.g., MacCrimmon and Ryavec 1967), and amplifies its effect where matching is to take place.

The uniqueness of materials and their destination locations, combined with the variability in duration and variation in execution quality of various steps in the supply chain allow for different ways to sequence material delivery and work area completion. In the cited, previous publications, the author described several alternative production systems and illustrated their impact on process execution by means of stochastic process models. One model reflected total lack of coordination between material delivery and work-area completion prior to the start of construction. A second model described perfect coordination. The corresponding materials staging buffers and construction progress were plotted based on output from discrete-event simulation models. A third model then illustrated the use of the lean construction technique called 'pull.' Real-time feedback regarding the status of progress on site was provided to the fabricator off site so fabrication process steps could be re-sequenced opportunistically. This yielded smaller buffers and earlier project completion and, when properly accounted for, increased productivity.

In contrast to this previous work, the present paper investigates how the use of standard materials might affect process performance.

Discrete-event Simulation Model with Standard Pipe Spools

A model of the pipe-spool installation process was developed and subsequently implemented using the STROBOSCOPE (Martinez 1996) software for discrete-event simulation. The symbols used in Figure 3 are explained in Appendix 1. The source code of this model is available upon request.

The rationale for selecting modeling elements and their parameters, detailed in Tommelein (1997a), reflects the aim of our study which is to illustrate the relationship between the use of various numbers of standard spools and process execution. Admittedly, such selections were somewhat arbitrary. For example, all variability in the model is centered around fabrication, rework, and transportation. Fabrication proceeds using cutsheets drawn from the CutSheet queue in random order. In contrast, off-site work (shown by the combination activity OffSiteWork in Figure 3), design (Design), on-site work (FieldWork), prerequisite work (PrereqWork), and final installation (Install) all have constant durations. In reality, of course, variability of the kinds shown here around fabrication can likewise manifest itself in these other activities, but we chose to model only a limited number of system features so that the model's behavior and output would remain tractable. Using the same methodology and tools, however, more complete and industrial-strength models can be developed.

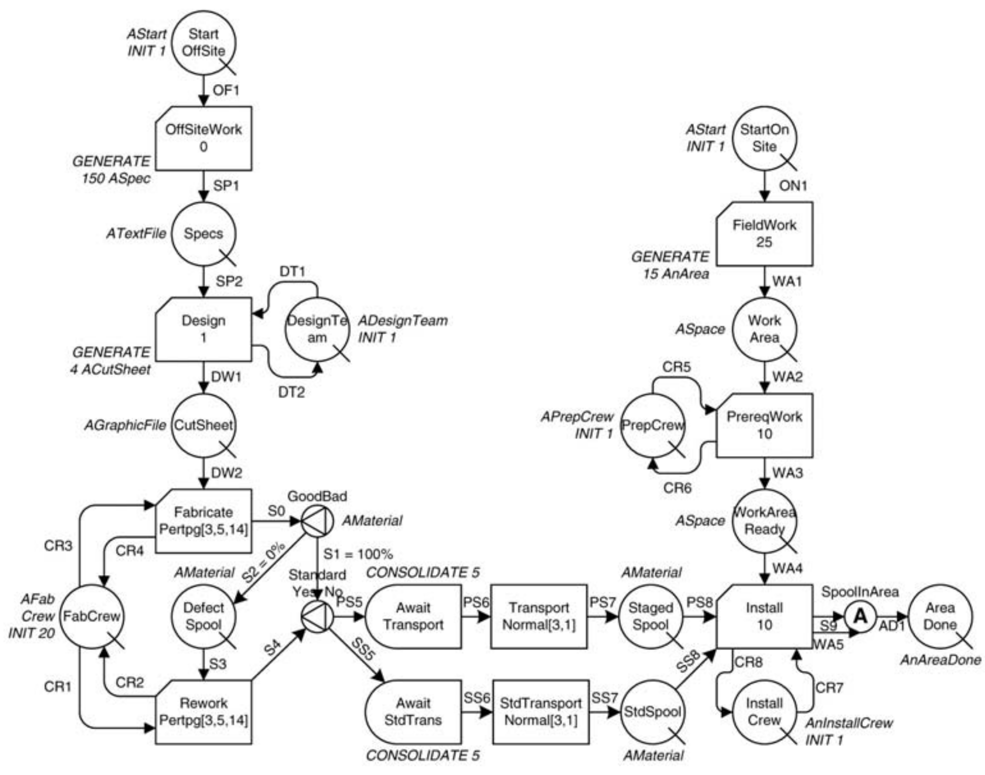

Figure 3: Process Model for Discrete-event Simulation of Pipe-spool Supply and On-site Construction

The process as depicted comprises two chains of activities: pipe spools are designed and fabricated off site while work areas are prepared on site. After spools have been shipped to the site, the chains merge when spools get installed in their designated areas. Pipe spools are fabricated off site according to the availability of engineering design information, the fabricator's plant production capacity, etc. Each spool is tagged individually to denote that it has unique properties, as shown in the project specifications, which also means that it has a designated destination in the facility under construction.

Spools are subject to inspection before leaving the fabricator's plant. The outcome of this activity is that a spool will be found fit-for-installation with an X % likelihood and, thus, there will be a problem with (100 - X) % of them. In the latter case, the fabricator must rework these spools to rectify the problem, prior to shipping. Rework on a spool is assumed to take about the same amount of time as fabricating a new spool. Due to space limitations in this paper, simulation output data from only selected production system configurations is presented. Specifically, the presented data is based on the assumption that no rework is needed: X = 100%, i.e., the GoodBad fork routes all spools through S1 and none through S2.

Standard spools are loaded to flatbed trucks (Figure 2) in one area, specific spools in another area, so they are shipped separately and in batches. The presented data is based on shipment batches of 5 spools per flatbed.

Concurrently with this off-site process, construction progresses on site. Roads are built, temporary facilities are brought in, foundation systems are put in place, structural steel is being erected, etc. Crews of various trades must complete their work in each area where spools are to be hung, prior to spool installation. When a specific set of ready-for-installation spools is available on site, and all prerequisite work in the matching area has been completed, spools can be installed. Completion of an area's installation work then signals to other trades that subsequent work can start.

Each of the 15 areas in the model requires 40 spools and each one of the 600-spool total could be unique. In previous work using the Pipe-spool Model, we included a scenario in which all 600 spools were identical (standard) and one in which all were unique (specific). We considered different sequencing strategies (e.g., perfect coordination vs. no coordination between off-site and on-site work) and then studied how this affected the project completion time (among other system characteristics). In this paper, the simulation experiment is to vary the number of standard spools per area (with each area having the same number of them), and the sequencing strategy assumes no coordination between off-site and on-site work. This means that spools will arrive in random order relative to the order in which areas are readied for installation.

By definition, even though a standard spool may have been 'ordered' (Design and Fabricate) for one area, it can be used in any area that requires it. For example, consider a setup with 5 standard spools per area. When InstallCrew is available to do work, any one of the areas ready for spool installation (WorkAreaReady) can draw 5 spools from StdSpool provided its 35 specific spools are available in StagedSpool (these spools need to be matched to their installation area). If several such areas are ready, the model draws them on a first-in-first-out basis from the WorkAreaReady queue.

PRESENTATION AND DISCUSSION OF SIMULATION RESULTS

Results of Nine Simulation Setups

The first setup of this model is based on the assumption that each area includes 0 standard spools (NrStandardSpools = 0). We recorded the project completion time resulting from the simulation. In order to capture the stochastic nature of this process, we ran 1,000 iterations with this setup and then computed the mean value and standard deviation of the resulting set of 1,000 project completion times. The second setup of this model is based on 5 standard spools per area (NrStandardSpools = 5), the third setup on 10 standard spools per area (NrStandardSpools = 10), and so on until NrStandardSpools = 40.

Figures 4 and 5 show how the project completion time is affected by the use of increasing numbers of standard spools. Table 1 summarizes the characteristics of the frequencies of occurrence of the project duration for each of the simulation setups based on 1,000 iterations. As is intuitively expected, when the number of standard spools per area increases, the process of matching spools to areas gets easier. It is then more likely to have all spools for a specific area on hand because (1) a smaller number of specific ones need to be on hand and (2) any of the standard spools supplied can be pulled for use in the area ready to be worked on. Consequently, the project duration shortens. Less intuitive is the pronounced, non-linear relationship that characterizes this phenomenon: as the percentage of standard spools increases, the project benefits disproportionately more both in terms of mean value as well as standard deviation.

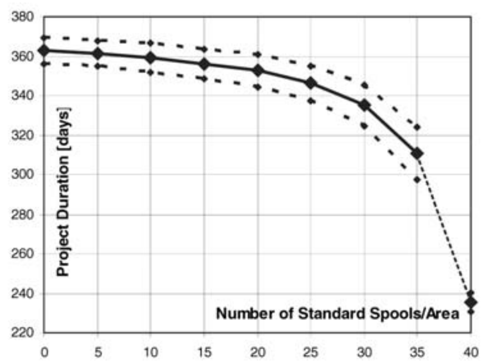

Figure 4: Number of Standard Spools per Area vs. Project Duration (mean value +/- standard deviation, 1,000 iterations per data set, no rework)

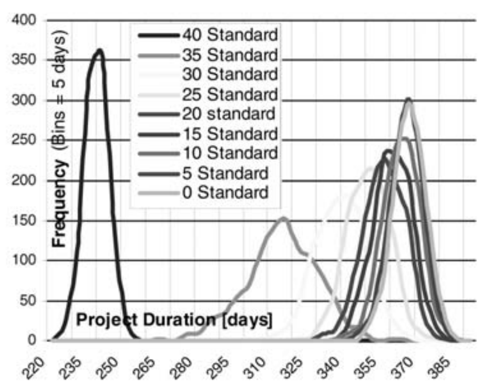

Figure 5: Frequency of Occurrence (using 1,000 iterations per data set and bins of 5 days) of the Project Duration for X Number of Standard Spools (NrStandardSpools)

	Number of Standard Spools per Area (NrStandardSpools)								
	0	5	10	15	20	25	30	35	40
5th Percentile [days]	351	350	347	343	339	332	318	286	227
Average [days]	363	361	359	356	353	346	335	311	235
95th Percentile [days]	373	372	370	368	365	359	352	334	243
Standard Deviation [days]	6	7	7	8	8	9	10	14	5

Table 1: Characteristics of Frequencies of Occurrence of the Project Duration for each Simulation Setup

These simulation results show some of the benefits of using standard materials instead of specific materials in project delivery. There are other benefits to using standard materials as well; however, these do not come to the fore because of the assumptions that have been made when developing the simulation model. We next describe observations from theory and practice to rationalize how the use of standard materials may further impact system performance.

Design

The model depicted in Figure 3 shows a duration of 1 for Design, denoting that the design team (DesignTeam) takes 1 day to work on each specification sheet (Specs) and develop 4 cutsheets (CutSheet). When standard spools are used in this process, fewer cutsheets have to be produced because, in effect, all standard spools of the same kind will refer to the same cutsheet. Therefore, when the number of standard spools per area increases, the design process is expected to shorten in duration.

On the contrary, this process benefit for the system overall will be smaller if the use of standard spools demands more time up-front for designers to develop the standard or if it means that more spools are be needed because the standard spools are somehow smaller. More spools would create more work in all downstream processes (Fabricate, Rework, (Std)Transport, and Install).

Fabrication and Rework

The model depicted in Figure 3 shows a duration of Pertpg[3,5,14][2] for the fabrication of each spool (Fabricate), meaning 3 days is the 5th percentile of the duration distribution, 5 days is the mode (most likely value), and 14 days is the 95th percentile. Because making multiple spools from the same cutsheet is repetitive, shop personnel is likely to get better over time at making those standard spools, thereby reducing the time needed to make each one. This 'getting better' (learning in a broad sense) is due to improved dexterity (learning curve effect) but more significantly to pursuit of opportunities to implement lean practices on the shop floor. Lean shop floor improvements might include reducing the setup and change-over time needed to start making standard spools, applying the 5S, standardizing the process, right-sizing equipment, and lining up work stations to facilitate flow (e.g., Allen et al. 2001). Results of 'getting better' include reduction in defects and thus reduction in the likelihood that rework would be needed. As was the case for design, when the number of standard spools per area increases, the fabrication and rework processes are expected to get shorter in duration.

Note that Figures 4 and 5 present data from models with no rework. If there were rework to be done after fabrication, then for any setup with a given number of standard spools, the

[2] Pertpg[a,b,c] refers to a probability distribution where 'a' is the 5th percentile of the probability density function, 'b' is the mode or most likely value, and 'c' is the 95th percentile. 'Pert' refers to the Program Evaluation and Review Technique (PERT) developed in the late 1950s to manage projects that have activities with uncertain durations. Roughly speaking, one might consider the 'optimistic' value in PERT to correspond to the 5th percentile in Pertpg, the 'most likely' value to the mode, and the 'pessimistic' value to the 95th percentile. 'pg' refers to the formulae Perry and Greig (1976) proposed, based on a reasoned approach, to replace the original, intuitively-derived PERT formulae. PERT was also critiqued by MacCrimmon and Ryavec (1967) because it ignores the merge bias effect.

project duration would be larger than the simulation results show. However, the overall trend of simulations that include rework (not shown here) exhibit a similar, non-linear and downward trend in project duration with increased use of standard spools similar to the trend shown in Figure 4. We speculate that the use of standard spools may be especially beneficial when the rework rate is high because the rate at which standard spools would have to be reworked is expected to be less than or at most equal to the rate at which specific spools would have to be reworked.

Installation

The model depicted in Figure 3 shows a duration of 10 days for the installation of 40 spools in an area (Install). Here too, if opportunities for getting better (learning in a broad sense) are taken advantage of and the installation crew gets better in the course of installing standard spools, the duration of Install may decrease as the number of standard spools increases.

Inventory Management

When all spools are unique and assuming a situation like the one modeled here, in which work off site is not coordinated with work on site, project managers may try to get as many spools to the site as soon as possible (though we do not recommend this approach). As the number of standard spools per area increases, the opportunity arises to use a different practice to manage the inventories of specific spools vs. standard spools on site. Fabricate could give priority to pulling standard spools from CutSheets in order to maintain a minimum number of spools in StdSpools so that at least NrStandardSpools will be available at any time Install could start. However, not many more than NrStandardSpools spools should be waiting in this queue. The determination of how many depends on the replenishing rate relative to the consumption rate of spools. Clearly, the shop should not make all standard spools first, as no work would get done until the specific ones were available on site to match an area. When many spools are standard, this would make for a huge number of spools, and beyond those needed for the next area to be worked on, one is not more useful than any other one. While maintaining a supply of standard spools, Fabricate can then further prioritize spools by area, first by taking those areas that are ready (WorkAreaReady) if such feedback from the site is available (e.g., using the pull mechanism described in Tommelein 1998).

Supply Chain Integration

In the model as presented, we have talked about spools that are standard within a project. Further benefits may be gained from using spools that are standard on multiple projects or standardized industry-wide. Upfront investment to develop a standard will pay off more when the standard is used on multiple projects. Especially firms that are vertically integrated, such as Shaw (Korman and Illia 2002) with capabilities in engineering design, pipe spool fabrication, pipe support fabrication, as well as installation, are in a good position to take advantage of such supply chain opportunities. Industry-wide standardization further makes it possible to involve outside suppliers in a project production system and thereby free up shop capacity or provide other project benefits where and when needed.

CONCLUSIONS

The work presented in this paper contributes to the body of research on the piping process by shedding light on the nature of a factor (product variety) contributing to the complexity exhibited in this process, and by illustrating means to manage this factor in order to reduce complexity. While the logic for the Pipe-spool Model was developed with industrial construction projects (process plants) in mind, readers may recognize the generic nature of the AEC process that has been modeled. Many construction processes require a combination of off-site and on-site work as prerequisites to final assembly. Resource flows or work streams tend to merge just prior to final assembly. Final assembly typically involves combining products, or combining one or several products with work-in-place. When products or work-in-place are unique, matching problems occur. In fact, matching problems are common in the AEC industry, although not necessarily recognized or known by that name. Managers may learn the lessons from the modeling experiments presented in this paper and apply them to any situation involving products and work-in-place that are unique.

In systems subject to variability, merging paths cause merge bias and the use of unique products further causes matching problems. In combination, they increase the likelihood of delay. The Pipe-spool Model confirmed what is intuitively expected in such systems, namely that there is a relationship between the number of standard products used in each area of a facility and the time needed to complete the project. The model also illustrated what is less intuitive, however, namely that this relationship is non-linear. As the number of standard spools per area increases, the project benefits disproportionately more. Thus, managers interested in using standard products will reap greater benefits when using the standard more broadly.

Matching problems are hard to solve when systems are combinatorial in nature and subject to stochastic variation, as is the case here. That is, many of these systems do not lend themselves to the formulation of closed-form mathematical solutions. Discrete-event simulation then proves to be not only a useful-, but in many cases the only tool available to describe and analyze such systems.

The model presented in this paper helps to sharpen one's intuition about the use of standard products; it also opens the discussion of how one goes about striking a balance between the degree to which uniqueness of products is pursued and the implications thereof not only on the value delivered by the final facility, but also on the process and on overall production system performance.

Some people may feel that using standard products is beneficial, while others may feel it introduces boring same-ness. Efforts at customizing products are justified when they are aim to increase value. More custom products may provide more desirable routing, lower energy use, etc. Using standard products simply may not be feasible. Recognizing the value to production of using standard products, research is in order to further develop means to study how products can be made more standard and how the use of standard products affects value delivered by a production system.

Whichever value system is being used, in the course of design (i.e., product design as well as production system design), the process costs and other implications of product choices all too often remain invisible. The simulation model presented here made some of these costs visible; specifically, it quantified one component of value delivered by the use of standard products, as assessed using project duration as the metric. Discussion of the model also highlighted that managers who decide on using and who develop standard products early in the design of a project—if not preceding the start of a project—may reap the benefits thereof in all stages of project delivery. While facilities operations and maintenance were not included in the model, they should be accounted for as well as the benefits of using standard products in these phases of project delivery could be significant.

Other simulation models could be run to further quantify value. Models could use hypothetical data, provided care is taken to use values that reflect the intended system being studied (Tommelein 1997a details industry practices and the rationale for selecting the values used in the Pipe-spool Model). More specific data from industry practice to populate simulation models might lead to further insights. Regrettably, such data appears to be sorely lacking. Further research is in order not only to quantify value and define metrics, but also to collect the data needed to characterize various steps in production systems.

The project-delivery situation as described in the Pipe-spool Model is by no means exceptional. Many of today's materials- and project management practices should be re-thought, and intuition sharpened about the detrimental impact variability has on project performance, so that project managers will know how to be more proactive when dealing with complex projects.

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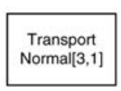
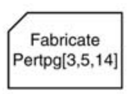
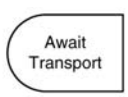
APPENDIX 1 – STROBOSCOPE SYMBOLS USED IN PIPE-SPOOL MODEL

Table 2 explains the simulation symbols used in Figure 3. Martinez (1996) provides more detail.

Table 2: Selected Stroboscope Symbols

SYMBOL	NAME	EXPLANATION
	**Queue**	Is a holding place (buffer) for 0, 1, or several resources waiting to become involved in the succeeding combination activity. Queues may contain generic or characterized resources. The latter are distinct from one another and they can be traced as individuals through various network nodes during simulation. The logic describing the ordering of resources upon entry into a queue of characterized resources is termed a DISCIPLINE. The order in which resources are drawn from a queue is programmed separately.
	**Normal (activity)**	Describes a certain type of work to be done, or a delay, of a known (probabilistic) duration from start to finish. May require a single resource or no resource at all.
	**Combi (-nation activity)**	Like a normal, describes a certain type of work to be done, or a delay, of a known (probabilistic) duration from start to finish. Unlike a normal, requires several resources in combination for its performance and draws what is needed from the queue(s) that precede it.
	**Consolidator**	Acts as a counter up to n (n is an integer value specified with the node): after n resources have been released into the consolidator, all n resources at once will be released from it.
	**Link**	Shows flow logic. Can be labeled to meaningfully describe the resources that flow through it. If the link emanates from a queue, a DRAWORDER may be specified to sequence resources being drawn from the queue.
	**Fork**	Describes a split in a resource's flow path. Incoming resources are routed along one path or another in a probabilistic or deterministic fashion, so the node is called a probabilistic fork or a decision node respectively. Each link emanating from it carries a likelihood or a statement evaluating to true/false for being followed by any specific resource arriving at the fork during simulation. The resource's actual path is determined at run time.
	**Assembler**	Shows that two or more incoming resources are being combined (assembled) into a single unit resource which is of the compound (a special kind of characterized) resource type.