MANAGEMENT OF PRODUCTION IN CONSTRUCTION: A THEORETICAL VIEW

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ABSTRACT

The transformation view and the flow view are two major conceptualizations of production. The current practice in construction is based on the transformation view. However, the transformation view is an idealization, and in a complex production situation the associated idealization error may become large. This is exactly what happens in practice. Task management, based on the transformation view, assumes that certainty prevails in production. However, it is widely observed that, due to the inherent variability of production in construction, intended task management degenerates into mutual adjustment by teams on site. It is argued that the transformation view and the flow view should be synthesized into a new theoretical view on construction. The inherent causes of variability in construction can be explained and the countermeasures for eliminating variability or stemming its impact can be pinpointed by this new theoretical view. It is shown that the Last Planner method is compatible with this new view.

KEY WORDS

Production theory, construction, project management, Last Planner.

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INTRODUCTION

Would we be better off if we had an explicit theory of construction? This question may seem trivial at first glance, however, in the framework of construction management as a discipline, there has been little emphasis on theory development. To clarify the question posed this paper endeavors to answer to two more specific questions: Which theoretical foundations exist for production? How should construction and methods used in it be interpreted from the point of view of a theory of production?

Due to space limitations, the discussion is highly selective. Construction design is not treated, even if design is almost always a part of construction production, construction being one-of-a-kind production. Production on site is emphasized, rather than production in the framework of the supply chain. From various production principles, the focus is on the variability reduction principle.

The paper is structured as follows: First, it is clarified why we need a theory of production and what it is. Next, two basic conceptualizations, transformation and flow, are reviewed, and the need for a synthesis is noted. After this, flows and transformations in construction production are analyzed. Finally, based on this analysis, design, control and improvement of production in construction is considered.

THEORY OF PRODUCTION

WHY DO WE NEED A THEORY OF PRODUCTION?

An explicit theory of production will serve various functions. A theory provides an *explanation* of observed behavior, and contributes thus to understanding. A theory provides a *prediction* of future behavior. On the basis of the theory, tools for analyzing, designing and controlling can be built. A theory, when shared, provides a *common language* or framework, through which the co-operation of people in collective undertakings, like project, firm, etc., is facilitated and enabled. A theory gives *direction* in pinpointing the sources of further progress. A theory can be seen as a condensed piece of knowledge: it empowers novices to do the things that formerly only experts could do. It is thus instrumental in *learning.* When explicit, it is possible to constantly test the theory in view of its validity. Innovative practices can be *transferred* to other settings by first abstracting a theory from that practice and then applying it in target conditions.

From the point of view of practice of production management, the significance of the theory is crucial: the application of the theory should lead to improved performance. In reverse, the lack of the application of the theory should result in inferior performance. Here is the power and significance of a theory from a practical point of view: it provides an *ultimate benchmark for practice.*

WHAT IS A THEORY OF PRODUCTION?

The primary characteristic of a theory of production is that it should be prescriptive: it should reveal how *action* contributes to the goals set to production. On the most general level, there are three possible actions: design of the production system; control of the production system in order to realize the production intended; improvement of the production system.

Production has three kinds of goal. Firstly, the goal of getting intended products produced in general (this may seem so self-evident that it is often not explicitly mentioned). Secondly, there are goals related to the characteristics of the production itself, such as cost minimization and level of utilization (internal goals). Thirdly, there are goals related to the needs of the customer, like quality, dependability, flexibility (external goals).

WHAT KIND OF THEORIES OF PRODUCTION HAVE BEEN PROPOSED?

PRODUCTION AS TRANSFORMATION

The transformation view of production has been dominant during this century. The conventional template of production has been based on it, as well as the doctrine of operations management. What is the related theory and how has it been translated into practice?

Theory

The transformation view has its origins in economics. A production theory based on the original view on production in economics (Walras 1952) has been proposed by Rolstadås (1995) and Wortmann (1992).

The starting point is "the Walrasian production model", which depicts the transformation process of production factors into finished product. The model is essentially made up of technical coefficients, which equal the ratio of transformation between the amount of a certain production factor and the amount produced of a given product. However, there are limitations with this model, and for overcoming these, three generalizations are made to it.

The first generalization of the Walrasian production model concerns the so-called Product graph (P-graph), by means of which the ordering of the product into assemblies, subassemblies and components (bill-of-materials) can be represented, as well as the sequence of operations (routing). The P-graph defines the work to be done.

The second generalization concerns organizational structuring of resources. These are described by the so-called R-graphs, which define how resources are combined and ordered into groups, departments and factories. Resources provide capabilities and capacities. Both group social structure and physical layout are covered in this generalization.

The third generalization extends the Walrasian production model to a dynamic control model, where three control activities are recognized: management of resources, management of products and coordination and synchronization (referring to the allocation of resources to products). These activities are considered on different time horizons.

Indeed, the interconnection between the P-graph and R-graph can be seen as management of production: "the purpose of management is to release and monitor work orders for production and engineering" (Rolstadås 1995).

Practice

The transformation model has been the conceptual foundation of scientific management, mass production (as it has been generally understood) and the modern corporation, which developed at the beginning of this century, and also of modern production control and project management, which have matured in the second part of the century.

According to Turner (1993), scope management is the *raison d'être* of project management. The scope is defined through the work breakdown structure. The purpose of scope management is defined by Turner as follows: (1) an adequate, or sufficient, amount of work is done; (2) unnecessary work is not done; (3) the work that is done delivers the stated business purpose.

Thus, it is obvious that the discipline of project management is purely based on the transformation concept and its principle of hierarchical breakdown.

PRODUCTION AS FLOW

The flow view of production, firstly proposed, as a scientific concept, by the Gilbreths (1922), has provided the basis for JIT and lean production. This view was firstly translated into practice by Ford starting in 1913; however, the template provided by Ford was in this regard misunderstood, and the flow view of production was further developed only from 1940s onwards in Japan, first as part of war production and then at Toyota. In the following, a number of crucial findings on the behavior and control of flows are shortly described.

Waste

The Gilbreths (Gilbreth and Gilbreth 1922) proposed to model flows as consisting of four stages: processing, inspection, waiting, and moving. From these, only processing is transformation, the others are not. Shingo (1988) indicates, that the improvement approach to these two types of stages is totally different; making transformations more efficient; trying to eliminate non-transformations. Thus, inspection, waiting, and moving represent *waste* in production.

Cycle Time Reduction

The basic improvement rationale in lean production is to compress the cycle time by eliminating non-value-adding time. The cycle time refers to the time required for a particular piece of material to traverse the flow. The cycle time can be represented as follows:

$$\text{Cycle time} = \text{Processing time} + \text{inspection time} + \text{wait time} + \text{move time}$$

Cycle time compression forces the reduction of inspection, move and wait time. In other terms, the basic thrust is to eliminate waste from flow processes. Thus, such practices as elimination of inventories, reduction of rework, short distances between work stations, etc. are promoted. In fact, this is the rationale of JIT production.

Little's Law

From Little's law (Little 1961), the following formula for the relation of cycle time and work in progress in any production line can be derived:

$$\text{Cycle time} = \frac{\text{Work in progress}}{\text{Throughput}}$$

Thus, by reducing work in progress, the cycle time is reduced, provided throughput remains constant.

Impact of Variability

In a breakthrough book, Hopp and Spearman (1996) show that by means of the queueing theory, various insights, which have been used as heuristics in the framework of JIT, can be mathematically proven. Maybe the most fundamental result regarding production control is that in view of a certain variability level in production, there is always a penalty in one form or another, even if the control is the best possible (Hopp and Spearman 1996). One has to select among three alternatives:

1. Buffering of flows (for increasing the probability that all parts are available at a workstation when needed), which leads to long cycle times and high WIP levels
2. Accepting lower utilization levels of resources, which equals acquisition of extra capacity
3. Accepting lost throughput (due to starvation of workstations).

Pull and Push

A further finding is related to the way of controlling the movement of material in the production system. Push systems schedule the release of work, while pull systems authorize the release of work on the basis of system status (Hopp and Spearman 1996). The underlying feature of the pull systems, like kanban, is that they establish a cap for work-in-progress, which, as Little's law shows, will also keep the cycle time in control. Beyond this, there are several other benefits associated with pull systems in comparison to push systems.

A production control system can also be a mixed push-pull system. Huang and Kusiak (1998) present a push-pull system that pushes through certain manufacturing stages and pulls elsewhere based on the characteristics of these stages. They argue that this is superior to a push system, while avoiding some inherent problems of pull systems.

SYNTHESIS OF PRODUCTION THEORIES

Up to the 1980s, production has been managed based on the transformation view. However, this foundation of production is an idealization, and in complex production settings the associated idealization error becomes unacceptably large. There are two main deficiencies: it is not recognized that there are also other phenomena in production than transformations; it is not recognized that it is not the transformation itself that makes the output valuable, but that the output conforms with the customer's requirements. Our focus here is on the first deficiency.

Factually, the transformation view addresses only the first of the three questions, posed by Turner above. The transformation concept is instrumental in discovering which tasks are needed in a project; thus it is perfectly possible to realize projects based on this view. However, the transformation concept is not especially helpful in figuring out how not to use resources unnecessarily. Instead, the principles of the flow view explain how, for example, the variability of production impacts on resource use.

These two views of production (Table 1) are not alternative, competing theories, but rather partial and complementary. Each of them focuses on certain aspects of the production phenomenon: the transformation concept on the value adding transformation; the flow concept on the non-value adding activities.

Table 1: Transformation and flow views of production

	Transformation view	**Flow view**
Conceptualization of production	As a transformation of inputs into outputs	As a flow of material, composed of transformation, inspection, moving and waiting
Main principles	Hierarchical decomposition; control and optimization of decomposed activities	Elimination of waste (non-transformation activities); time reduction; variability reduction
Methods and practices	Work breakdown structure, MRP, Organizational Responsibility Chart	Continuous flow, pull production control, continuous improvement
Practical contribution	Taking care of what has to be done	Taking care that what is unnecessary is done as little as possible
Suggested name for practical application of the view	Task management	Flow management

What is needed is a production theory and related tools that fully integrate the transformation and flow concepts. As a first step towards this, we can conceptualize production simultaneously from these two points of view. In the transformation view, the basic thrust is to define the task (work) to be done, and to get it done efficiently. In the flow view, the basic thrust is to eliminate waste from flow processes.

Next, it is analyzed how such a simultaneous consideration of the transformation view and the flow view can be ensured in construction.

APPLICATION OF TWO THEORIES OF PRODUCTION TO CONSTRUCTION

FLOWS AND TASKS OF CONSTRUCTION

The production in construction is of assembly-type, where different material flows are connected to the end product. In Table 2, the material flows of construction are depicted and contrasted with those of car production. In car production, the material flows can be divided into two types, the flow of components to the assembly line, and the (main) flow of the car body through the assembly line. In construction, there are three flows. The material flow of components to the site is comparable to that of car production. However, due to the size of the product of construction, there is an intermediate workflow where all installation locations proceed through the installation workstation (Birrell 1980). Let us call it the location flow. In car production, this phenomenon exists also (several seats have to be installed in different places of the car body), but due to the compactness of (ordinary) cars, all seats can be installed as one operation at one workstation. Lastly, the building frame proceeds through the different assembly phases (referring to processing of all locations by a workstation), like a car proceeds through different workstations. Again, a building is immobile, contrary to a car body.

Let us illustrate the cost significance of each flow through an example (Tanhuanpää et al. 1999). In a recent office building project in Finland, the costs of materials bought and transported to the site, corresponding to the material flow, were 45% of the total construction costs (design costs included). The cost share of work on site, caused by the location flow, was 35%. The time-dependent building costs, essentially caused by the assembly flow duration, were 6% of the total construction costs. However, when the opportunity and other costs for the owner are taken into account, the time-dependent costs were 12 % in comparison to the total construction costs. Note that all these costs have a cost share due to waste, which provides a potential for improvement.

Table 2: Material flows in car production and site construction. The components of seat and window are used for illustration. The concept of task is presented for comparison.

	Car production	**Site construction**
Material flow (supply chain)	A seat is assembled in the seat factory, transported to the car assembly factory, transferred to the workstation and installed.	A window is assembled in the window factory, transported to the site, transferred to the place of installation and installed.
Task (elementary)	*The seat installer installs the seats at his workstation to one car.*	*The window installation team installs one window (sometimes two or more) to one window opening.*
Location flow	The same as above (the seats of one car are installed as one task at one workstation)	All window openings proceed through the workstation (in practice, the team moves throughout the building).
Assembly flow	The car body moves through all assembly workstations of the production line.	The building proceeds through all assembly phases.

INTERACTION BETWEEN FLOWS AND TASKS

Let us analyze the interaction between these three flows and tasks in construction. We focus especially on the elementary construction task, as it repeats from location to location and from trade to trade. A work order (or assignment) consists of a certain number of tasks to be carried out in a certain location in a certain time window.

Construction Tasks are of Assembly Type

Firstly, it has to be noted that *a construction task is (usually) an assembly operation*. If an assembly operation involves multiple purchased parts, the reliability of deliveries is extremely important, because the probability of having them all at time is the product of the individual on-time probabilities (Hopp and Spearman 1996).

In Figure 1, the preconditions for the execution of a construction task, like a day’s work, are presented. The inputs to a construction task are evident. There are at least seven resource flows (or conditions) that unite to generate the task result (usually even more, if more than one material is used in the task).

Many of these resource flows are of relatively high variability (due to construction peculiarities), and thus the probability of a missing input is considerable. For example, it is not uncommon that detailed drawings are still lacking at the intended start of the work. Latent errors in drawings or prefabricated parts will surface as problems of realization on site. External conditions (extreme temperature, rain, snow, and wind) form one specific source of variability. Also, the productivity of manual labor is inherently variable, and the availability of space, made free by other teams, is thus bound to be variable. Thus, in contrast to typical manufacturing, there are more sources of variability.

Let us assume that the probability of a deviation in any of the resource flows to a construction task over one week (5 workdays) is 5 %. The probability that there is no deviation in any input flow is thus (Hopp and Spearman 1996):

$$\text{Prob}\{\text{no deviation in any input flow}\} = (0{,}95)^7 = 0{,}70.$$

In fact, empirical observations of the realization of assigned construction tasks during one week give the result that a value less than 60 % of plan realization is quite normal (Ballard and Howell 1998).

Thus, the first insight gained is that construction consists of assembly operations involving a high number of input flows. Planning and controlling production so that the workstations do not starve due to lack of inputs is an inherently difficult task. This is the very reason why tasks and flows have to be considered parallelly in production management: *the realization of tasks heavily depends on flows, and the progress of flows in turn is dependent on the realization of tasks.*

This insight is reflected in the observation on high levels of non-productive time as typically found in construction. However, one often tries to cope without all prerequisites, if possible; this will be discussed below.

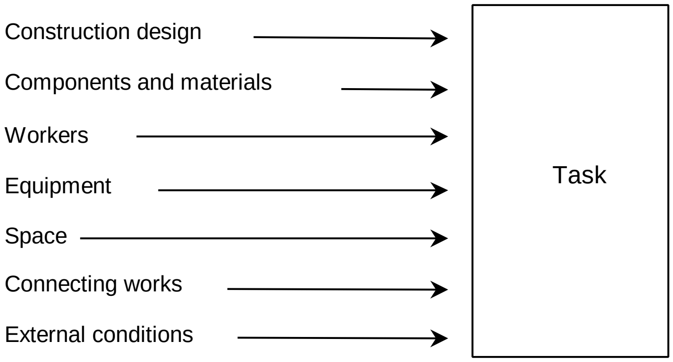

Figure 1: The preconditions for a construction task

Construction is Prototype Production

The second insight concerns defects. *Construction can be conceived as prototype production, which normally is carried out for debugging errors in design and production plans* (Methodik 1986). In fact, due to the one-of-a-kind nature and temporary organization, drawings and production instructions are the most frequent cause of construction defects. The resulting rework is, of course, a source of further variability.

There is Part Congestion and Workstation Congestion in Construction

Usually congestion refers to a situation where there are parts around a workstation either waiting to be processed or to be transferred to the next workstation. It is easy to find such congestion in construction, too. However, regarding location flows in construction, it is the installation team that moves from location to location. This leads to the third important feature of construction. In factory production, one part can physically be at one workstation at the same time. However, in construction, *one location (say, a room) can be worked on by* *several workstations at the same time*, usually with lessened productivity due to interference. Thus, in addition to part congestion, workstation congestion may occur in construction.

Work is Done in Suboptimal Conditions

However, workstation congestion is just one facet of a wider phenomenon. It is natural that when a workstation is on site, work that happens to be available is carried out. Thus, tasks are routinely commenced or continued without all preconditions realized. The fourth insight gained is that *work is often done in suboptimal conditions, with lessened productivity*. This is a type of waste characteristic of construction, not present in the classical list of seven wastes originating from manufacturing.

These non-optimal conditions include especially the following (Ballard and Howell 1998, Jensen et al. 1997, Josephson 1994): congestion, out-of-sequence work, multiple stops and starts, inability to do detailed planning in advance, obstruction due to material stocks, trying to cope without the most suitable equipment for the task (lack of planning and preparation), interruptions due to lack of materials, tools or instruction**,** overtime, oversizing crew.

One specific source of non-optimal conditions is rework, in which one usually has to remove or demolish the defective structure or component. This may lead to dilution of supervision (Finke 1998), and consequently rework is carried out without much planning and preparation

DESIGN, CONTROL, AND IMPROVEMENT OF PRODUCTION IN CONSTRUCTION

Up till now, we have found several interesting features in production of construction; however, they all are potentially prone to cause or amplify waste. What can be done to stem the formation of waste?

PRESENT STYLE OF PRODUCTION MANAGEMENT IN CONSTRUCTION

It is useful to consider how presently production management is taken care of in construction. The customary approach is to prepare a master schedule that is used as a basis for plans of more specific nature, like purchasing or manpower plans, and for more detailed, short-term plans. However, in practice, the impact of variability is often so strong, that the master schedule becomes obsolete. However, updating of the master schedule is usually deficient, and consequently task management, at the short term, is largely done informally by the foremen or left to the teams on site to be taken care of by mutual adjustment. Thus, as Laufer and Tucker (1987) have formulated, the role of planning is transformed from initiating and directing action before it takes place (as suggested by theory) to influencing and regulating operations while in progress (as intended in practice) and to follow-up and status reporting (as realized in practice).

Thus, in current construction practice, the intended task management degenerates into unsystematic action. Flow management is not addressed in an orderly way in the first place, but is being realized as a side-product of task management.

COST OF VARIABILITY

Thus, it seems that in addition to the inherent characteristics of flows and tasks, bad control adds to the variability of construction. What is the cost of this variability?

As discussed above, for production control, in view of a given variability level, there are three generic, optional penalties: buffering of material flow and workflow, lower utilization of resources or lower production (due to starvation).

Buffering is routinely—even without consideration of whether a need for it exists, as observed by Ballard and Howell (1998)—used in construction, both in the sense of material flows and assembly flows (time and space buffers between adjacent teams). Material stocks lead to multiple handling, material loss due to theft, rain, handling error etc., obstruction to work and added financial costs. Buffers in the assembly flow determine the construction duration; added duration leads to added time-dependent site costs, financial costs and lost opportunity costs (lost rent).

Lower utilization of resources is rarely used as an intended strategy. Instead, lower production, due to starving, can commonly be found; it is reflected in the high share of waiting time by men and machines, as typically found in time studies. Of course, it adds to work and machine costs.

However, in construction there seems to be a fourth alternative: accepting lower productivity due to working in suboptimal conditions. Working in suboptimal conditions is very common in construction. Beyond lower productivity, there are several indirect disadvantages. It is more difficult to achieve the intended quality level. Working in suboptimal conditions is more accident-prone. The amount of physical waste tends to grow.

In addition to production proper, there is usually much waste in the material flows of the supply chain, caused by bad control and variability (Vrijhoef and Koskela 1999).

Thus, indeed variability is also costly in construction.

REMOVING VARIABILITY AND STEMMING ITS IMPACT

There are three levels of encountering variability: design, control, and improvement of the production system (note that supply chain management is not addressed here; of course, it too provides a major potential of cost and time reduction).

System Design

The most basic solution is to eliminate these problems on the level of system design. The site problems can be alleviated by configuring the material flows so that a minimum number of activities are carried out on site. The rationale of prefabrication, modularization and preassembly is partly based on this principle. The problems stemming from the one-of-a-kind features can be alleviated by using standard parts, solutions etc. Interference between tasks can be reduced through procurement strategies such as the French sequential procedure, where there is always only one company working on site.

Production Control

The next option is to mitigate the inherent variability on the level of control. Regarding every individual part of the work flow, we want to accomplish the following: avoiding excessive buffers; avoiding lost production; avoiding working in suboptimal conditions; avoiding the cascade of pointwise deviation to other tasks.

A new method, often called Last Planner, to cope with the situation met in construction production control (and improvement), has been developed by Ballard and Howell (1998) since 1992. There are five basic principles in this method.

The first principle is that the assignments should be sound regarding their prerequisites. This principle has also been called the Complete Kit by Ronen (1992). The Complete Kit suggests that work should not start until all the items required for completion of a job are available. Thus, this principle pursues the minimization of work in suboptimal conditions.

The second principle is that the realization of assignments is measured and monitored. The related metrics, Percent Plan Complete (PPC), is the number of planned activities completed, divided by the total number of planned activities, and expressed as a percentage. This focus on plan realization diminishes the risk of variability propagation to downstream flows and tasks.

The third principle dictates that causes for non-realization are investigated and those causes are removed. Thus, in fact, continuous, in-process improvement is realized.

The fourth principle suggests maintaining a buffer of tasks which are sound for each crew. Thus, if the assigned task turns out to be impossible to carry out, the crew can switch to another task. This priciple is instrumental in avoiding lost production (due to starving) or reduced productivity (due to suboptimal conditions).

The fifth priciple suggests that in lookahead planning (with time horizon of 3-4 weeks), the prerequisites of upcoming assignments are actively made ready. This, in fact, is a pull system (Ballard 1999) that is instrumental in ensuring that all the prerequisites are available for the assignments. On the other hand, it ensures that too great material buffers do not emerge on site.

Production System Improvement

Regarding improvement, we want to locate the source of variability, to launch corrective action, if feasible, and to monitor to what extent the corrective action has been performed. In fact, the method of Last Planner is instrumental for these purposes, as evident from the description above: it effectively combines control and improvement to fight back against variability and the waste caused by it. However, it is possible also otherwise to require increased reliability of deliveries, added conformance to schedule from subcontractors, etc. Note that in proportion as flow and task variability is reduced, the duration of the assembly flow can be shortened.

CONCLUSIONS

Traditional task management assumes a certain production process. In practice, due to the inherent variability of production in construction, intended task management degenerates into mutual adjustment by the teams on site. However, by the various methods of flow management, the adverse impact of variability on tasks can mitigated. In reverse, a tighter task management contributes to flow reliability. The method of Last Planner turns out to combine central elements of task management and flow management for production control in construction.

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