CONSTRUCTION PHYSICS

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ABSTRACT

At the 14th annual conference in the International Group for Lean Construction in 2006 the authors presented the concept of construction as a process being fed by a number of flows out of which one is the critical one deciding the speed with which the process takes place. This contribution takes the idea further and sets out by discussing production in general and the underlying mental flow models associated with this understanding. It then suggests a new model for the understanding of the nature of project production with a focus on all the flows feeding this complex process. It continues by discussing the nature of the flows and at the same time looks at the impact of their variability at the project level. And finally it looks at the present tools for project management and their suitability in a process understanding of the project where particularly the nature of Last Planner is discussed.

KEY WORDS

Construction physics, flow, project management, mental models

INTRODUCTION

Understanding and managing the construction process as a flow have been a key issue for IGLC since its very first meeting in 1993. Sources for inspiration have been Shingo (1989) and the Toyota Production System (Shiomi and Wada, 1995; Ohno, 1988) along with its Western interpretation as Lean Production (Womack et al, 1990; Womack and Jones, 1996). But also much earlier sources have been influencing the IGLC thinking such as Aristotle (app. 330 B.C.) and not least the interpretation of his work as presented by Koskela and Kagligou (2005 and 2006). In between these two – in time very widely spread – contributions, we find the principles from the Ford production system (Ford and Crowther, 1988) as well as the work of Gilbreth and Gilbreth (1922).

Within the IGLC framework it is not least the work of Koskela (1999, 2000), which represents the basis for the flow understanding of the construction process along with the work of Ballard (2000) where an approach to flow management in practise is introduced under the term: Last Planner. Bertelsen and Koskela (2002) suggested that Koskela's TFV theory (Koskela, 2000) may be a new framework for

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construction management. Later reports from practise show that this is the case (Elsborg et al, 2004). Understanding and managing the flow seems at the same time to be an increasingly important issue, which more and more is understood as a social process, a viewpoint advocated by Macomber and Howell (Macomber, 2001; Macomber and Howell, 2003, Howell et al 2004, Howell and Macomber, 2006), which may require a new and deeper understanding of the nature of the construction process as a number of flows jointly generating value for the client.

We have named this understanding: *Construction Physics*.

CONSTRUCTION PHYSICS

The inspiration for the development of Construction Physics in the light of the work within the IGLC came from Hopp and Spearman's work on Factory Physics, which uses flow, variability and queuing theory disciplines to rationally and mathematically model and understand the flow in the mass production processes. A fundamental issue in Factory Physics is to understand the underlying causes of time and flow variability mainly caused by non-transformation stages of production e.g. waiting, moving, inspection etc (Gilbreth and Gilbreth, 1922), and to characterize the effects of this variability in the overall production process. Hopp and Spearman (2001) developed a set of laws that govern how flow systems behave by means of queuing theory. Using these laws it is possible to analyze the effect of variability on performance.

The original idea for the work on Construction Physics was to do the same for project production looking not at the main flow of the product only, but – inspired by Goldratt (1997) who shows that there may be more than one flow deciding the process performance – looking at the whole construction process as a process being fed by several flows. The basis for Construction Physics was supposed to be adopted from previous IGLC research on the individual flows and their management.

However, it was soon found that even though this approach may be feasible in a longer perspective, the complexity of the process being studied and its true nature is not at all so well understood that we for the time being dare set up managerial principles or indeed mathematical models of the process discussed, as done by Hopp and Spearman (2001).

The paper therefore limits itself to a discussion of the nature of the construction process from a process perspective and to briefly discuss the validity of the management tools and principles most widely used in today's practice.

The paper is a contribution to an ongoing research project on the understanding of flow in construction. Other contributions from this work are Koskela et al (2007); Rooke et al (2007 and Bertelsen (2007), all contributions to IGLC 15 as well. The aim of the paper is to provide a deeper insight and provoke thinking by a new mental model of the construction process as a basis for further studies of the working of our management tools. The question of a Construction Physics is thereby opened, some ideas like *Critical Flow* have been introduced, and it is expected that in the years to come this understanding may lead to improved instruments for the managing of the construction processes.

UNDERSTANDING FLOW IN PRODUCTION

In the context of Lean Construction the outset for understanding the construction process is often Koskela (2000) where the nature of production is discussed from three different perspectives: Transformation, Flow, and generation of Value. In the setting of this paper the flow is the important aspect because it is the flow and its nature that causes the need for Construction Physics. But what does flow mean in production – mass or project?

MASS PRODUCTION

While Hopp and Spearman (2001) look at the flow of the product mainly, which is a one line flow rather easy to comprehend, Shingo (1989) argues that production has two distinct and intersected types of flows: Process and Operation[5]. They can be characterized as a system on two axes, where the 'process flow' axis represents the development of the object being produced; i.e. the change taking place in the material being worked on and thus the flow that generates the value, whilst on the 'operation flow' axis we find the operations, the elements of the production, being performed on the product by workers and machines. At the same time Shingo (1989) criticizes the traditional way of understanding production (and thereby the underlying model for Hopp and Spearman's work), which considers process and operations as differing in size of units of analysis only. By this view agues Shingo, process and operations lie on the same axis what wrongly leads to the assumption that improvements made at the operations level necessarily lead to improvements of the process as a whole.

Shingo does not deal with the aspect of value as such – the product value seems in his work to be an imbedded feature in the product design – but looking at his model trough the spectacles of the TFV understanding we may recognize that Value is the outcome of the process, which again is relying on its flows of operations.

PROJECT PRODUCTION

Even though mass production becomes more and more customized it is still a production based upon the mass production's ordered – laminar – flow. All product variations and customizations are foreseen and included in the product and production system designs making the room for real improvisation in the product or process features at the most very limited and in most cases non-existing. Thus the production system is by and large the same for all the product variations.

[5] Unfortunately this introduces a new, specific meaning to the terms *Process* and *Operation*, which are otherwise quite often used in a general meaning. Koskela (2000) discusses *Flow* and *Transformation*, which sounds the same as *Process* and *Operation*. However, *Transformation* is the value generating operations only, while *Operation* in Shingo's universe is anything being done to the product by men and machines, i.e. transport, inspection and waiting as well. Also Shingo sees *Operations* as the outcome of a different set of flows. Rooke et al (2007) take this argument even further by focusing on the importance of the flow of operations.

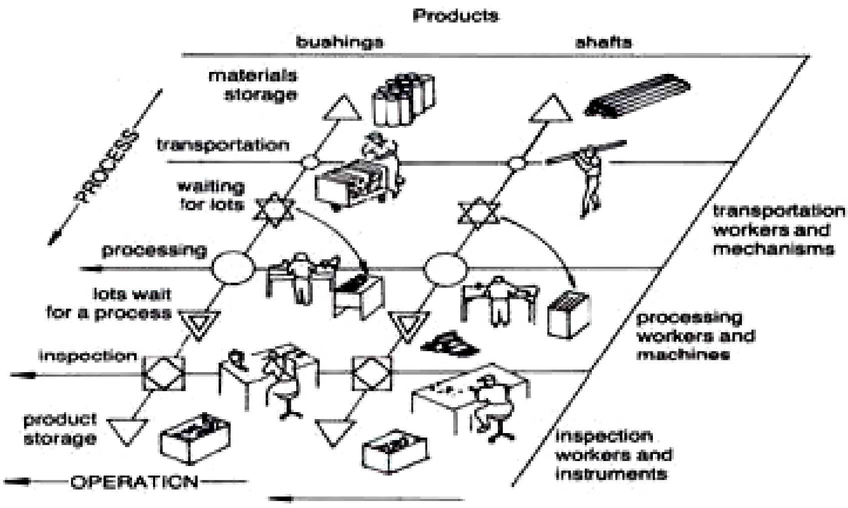

Figure 1: Shingo's Production Model showing production as two Flows (Shingo, 1989)

Project production is just the opposite as it is the production of truly one-of-a-kind products, where all the options given by the laws of God and the authorities are open for the designer and his client. Consequently, the production system must be designed and organized accordingly, which means that we seldom see the same production system twice. Even though a lot of the parts entering project productions such as construction are standard or mass produced, most of the assembly and quite a lot of the parts are the outcome of craft, which is delivered by an ever growing number of specialist contractors and designers.

The construction process therefore differs from manufacturing not only in terms of size and immobility of the product (Birrell, 1980; Koskela, 2000) but also through the nature of the process. Although being based on the same premises as Shingo's, production flows in construction are characterized by not only having a process where products are passing workstations, but also by having a flow of workstations (workers, equipment, etc.) executing the different operations at different locations around the product. This means that also issues such as space for work, storage, access etc may be seen as flows.

This leads us to recognize two different types of flow: The *Process flow*, which is the main objective and which at the end of the day delivers the value to the costumer, and the *Operations flow*, which at any step in the process generates the basis for the process itself to take place as foreseen.[6]

Traditionally, the construction industry has been very focused on the operations flow. Operations are what is purchased through the prevailing contracting practice and what is in the focus of the project management. As stated by Gregory Howell at the IGLC 8 in 2000: *Project management does not manage projects, but contracts.* This focus on operations – by project management through contracting practice and by trade contractors because providing operations is their rationale for doing business,

[6] This model will later be discussed in more detail.

along with the efforts of the suppliers of equipment and materials leads to improvement on value-adding-activities – the transformations – primarily. However, this approach often generates huge amounts of waste as non-value-adding activities as well, involving large quantities of resources (Santos, 1999)[7]. Therefore Shingo's approach to identify the value stream, identifying non-value-adding operations and to minimize or even eliminate them, before trying to improve the operations themselves is of importance for the construction process (Shingo, 1989; Koskela, 2000).

PROJECT MANAGEMENT

The project management's focus on the operations mainly is a well known and often observed situation; but what is really the project management's underlying picture of the construction process they are managing?

Since the 1960'ies the prevailing way of showing the project process has been the CPM chart (figure 2), which shows the flow of tasks to be performed – and does so from left towards right, even though the building as such is a fixed item not moving as the product is in Shingo's model (figure 1).

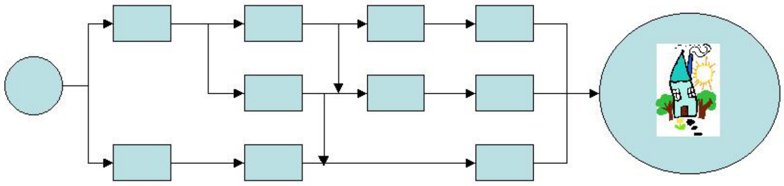

Figure 2: Critical Path Method plan

Other ways of showing the project production process are the often used Gantt Chart which is easier to read and comprehend and at the same time makes it possible to see, which crew are taking hand of which tasks. But at the same time the Gantt Chart makes it more difficult to analyze the dependencies between the activities (figure 3).

The Line of Balance (LOB) is an old way of showing flow. It was originated by the Goodyear company in the early 1940'es and was developed by the US Navy in the 1950'es.[8] It elegantly shows the combination of tasks, crews and space and does so in an easy to understand way. However, the underlying assumption is a fairly stable production situation where the flow of the other operations needed for the process is reliable. An early (earlier than Goodyear?) and very successful application was indeed the preparation of train tables.[9] One may argue that LOB is looking at the flow, but at the flow on the site only, as the issues dealt with only comprises flow of crew and to some extent the flow of space, assuming that the flow of the previous work has been performed as stated in the plan and that the flows from the outside i.e. the flow of information, materials, new crews and approvals take place as foreseen. (figure 4)

[7] Indeed, Shingo (1989) argues that this understanding may often lead to improvement in efficiency in non-value-adding activities which from a process perspective may easily be eliminated and thus they are only making the 'generation of waste' more efficient.

[8] http://www.iit.edu/~aliss/history.htm

[9] The first author remembers an early paper form the Danish State Railroads on this use. As it was met during the last years of his study in around 1959, it may easily have been from before World War II.

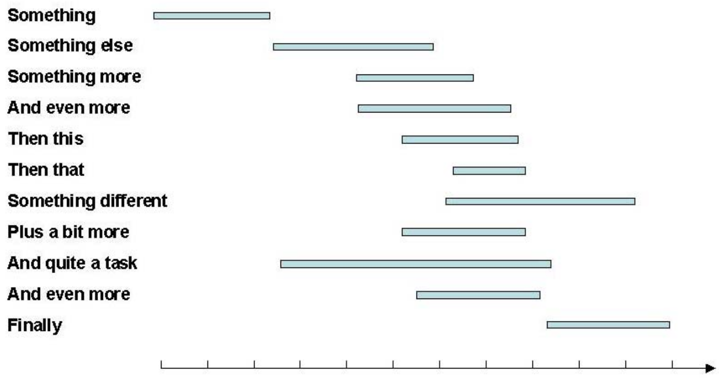

Figure 3: The Gantt Chart

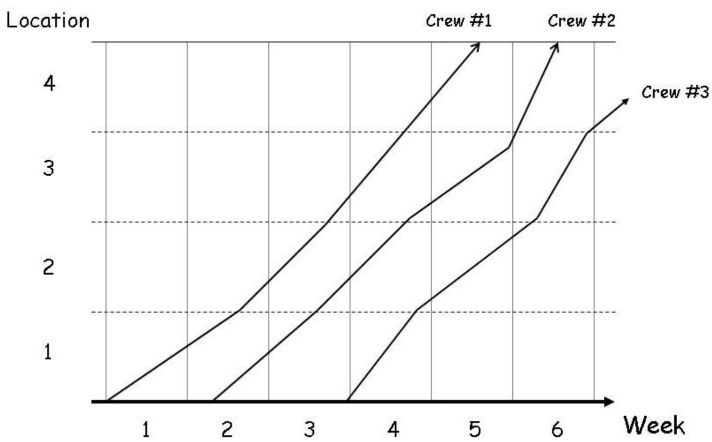

Figure 4: Line of Balance

Recently some attempts to understand and demonstrate the process by means of 4D CAD models have been made (Cooper et al, 2004). Looking closer at these models, they all express the thinking of construction as a series of operations. The flow perspective is at the best very indirectly dealt with. Therefore, no matter how useful these tools have been for project management our argument is that they do not show the true nature of the process the project manager is dealing with in the day to day management of his project, and that they therefore may obscure the understanding of how to really manage projects.

THE PROJECT AS A PROCESS

As shown, the project has for some time been seen as series of operations mainly. In the light of the flow understanding we suggest that we in stead try to look at projects in the same one-eyed way – but now from the flow perspective. Not to change radically the way we conduct projects, but in order to understand the nature of the phenomenon from a different perspective, and maybe through this approach reach a deeper understanding of the nature of project production. Our proposal is therefore to see the project as a true process where the nature of the process itself and not least of the flows feeding it is put into focus and where the importance of the parts – the operations – is tuned dramatically down. This mental model may or may not be as useful for the project management as the operations model expressed in the Gantt Chart, the CPM plan or the LOB schedule, but it is indeed much more suited for understanding the real nature of the project and of the environment in which the construction project is operating.

Our first attempt to understand this was to see the construction as a flow of work being fed by a number of flows – like a major river with its tributaries (figure 5).

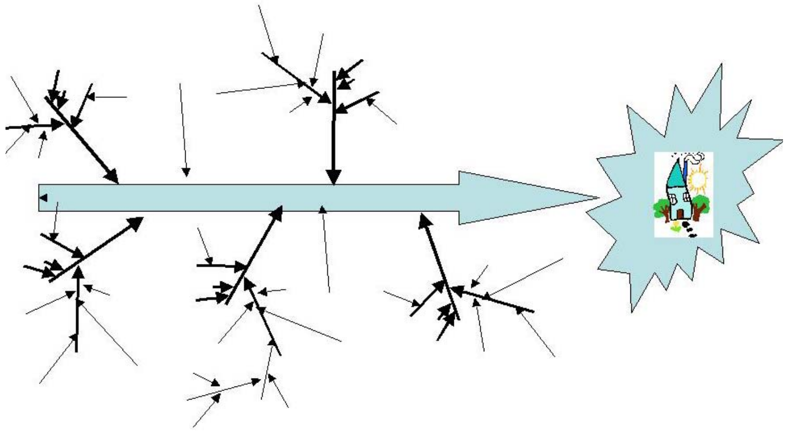

Figure 5: The River Model

This model expresses the flow nature better, but based on recent management experience (Elsborg et al, 2004, BygSoL, 2007) we have the feeling that even this model does not show the true nature of the process. The authors have therefore between themselves and with colleagues discussed which well known mental models would be better to describe the pure process thinking. The simple and best known process which we are all familiar with is probably that of fire. Fire is a process where combustible material is oxidized at high temperature in a process requiring heat, which is most often produced by the process itself. The fire also often requires a kind of space in order to keep the whole process together.

Using this model in the case of fire, we have two kinds of flows feeding the process: One or more flows of combustible material, and one of oxygen. And we have heat as the outcome of the previous process steps or at the outset as a third flow. Then we have the space – the furnace – where he process takes place. The construction process is indeed more complex but we still get a complete new view by this thinking (figure 6).

If we want to control the process of fire, our task is not to control the process itself as much as managing one or more of the flows. Most often we will do so by reducing or increasing the supply of oxygen or fuel in order to turn down or increase the intensity.

However, this simple mental model does not explain the complex nature of the construction process as neither do our other discussed models such as the growing oak or the chemical reactor. But they all show the same nature of a process: It is a point based phenomenon fed by a number of flows, out of which one – and only one at any given time – is the *critical* flow. In the case of the fire, no matter how much fuel one pumps in, it will not catch up speed without at the same time getting the oxygen and heat needed. In this situation either oxygen or heat is the critical flow and the excess fuel is waste.

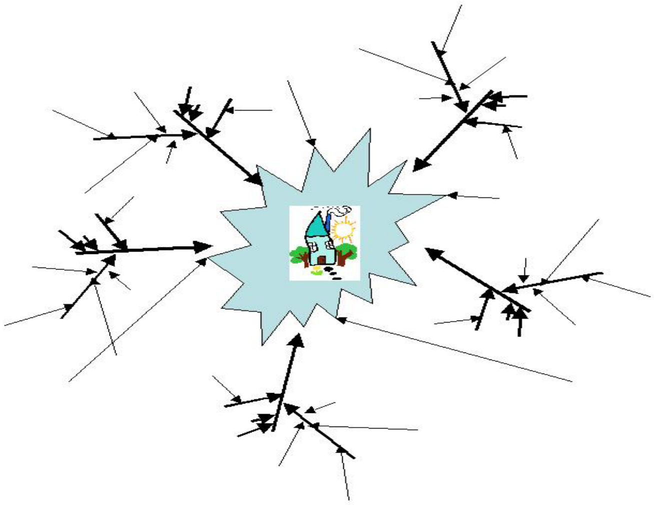

Figure 6: A True Process Model

A similar situation exists in a project, where a number of flows such as previous work, crew, information, materials etc are feeding the process. The really new observation made by this flow model as compared to the operations usually used is, that previous work is just one flow among several (figure 6). But which are the other flows in the construction process?

CONSTRUCTION AS A PROCESS

Koskela (2000) made the observation that any construction work package (task) has seven preconditions in order to be 'sound' – that is, that it can be undertaken without any delay, which is an important issue in the Last Planner System (Ballard 2000). Koskela suggested the preconditions to be: Construction design (information), Components and materials, Workers, Equipment, Space, Connecting (previous) works, and External conditions (figure 7), and he went on to demonstrate that a reliability as high as 95 percent in each of the flows would cause a reliability of app. 70 percent only on the soundness of the work package itself. The objective of this observation was not to understand the nature of the flows as such but to demonstrate the impact of the variability in the flows on the process itself only.

Another model of the flows in the construction process was introduced by Ballard et al (2002), who looked at the nature of the prerequisites for the process and found three types: Directives, Previous work, and Resources: "*Directives provide guidance according to which output is to be produced or assessed. Examples are assignments, design criteria, and specifications. Previous work is the substrate on which work is done or to which work is added. Examples include materials, whether 'raw' or work-in-process, information that is input to a calculation or decision, etc. Resources are either labour, instruments of labour, or conditions in which labour is exercised.*

Resources can bear load and have finite capacities. Consequently, labour, tools, equipment, and space are resources." (Ballard et al 2002)

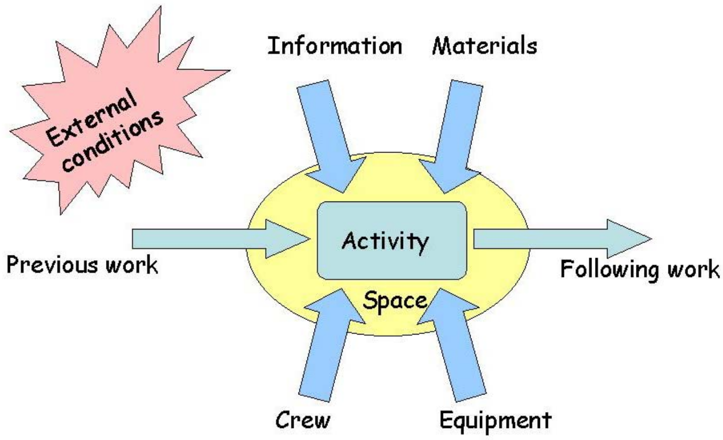

Figure 7: The seven Flows (Koskela, 2000)

Their aim seems to be to understand the nature of the flows deeper – not in an operational management perspective as much as the flows themselves. Their idea of grouping the seven – or even more – flows into three main streams is quite elegant for the theory, as it simplifies the study of the nature of the process.

Directives are obviously issues outside the project management's control. They form the framework like the laws of chemistry in the above fire model. It is within this framework the project has to be conducted.

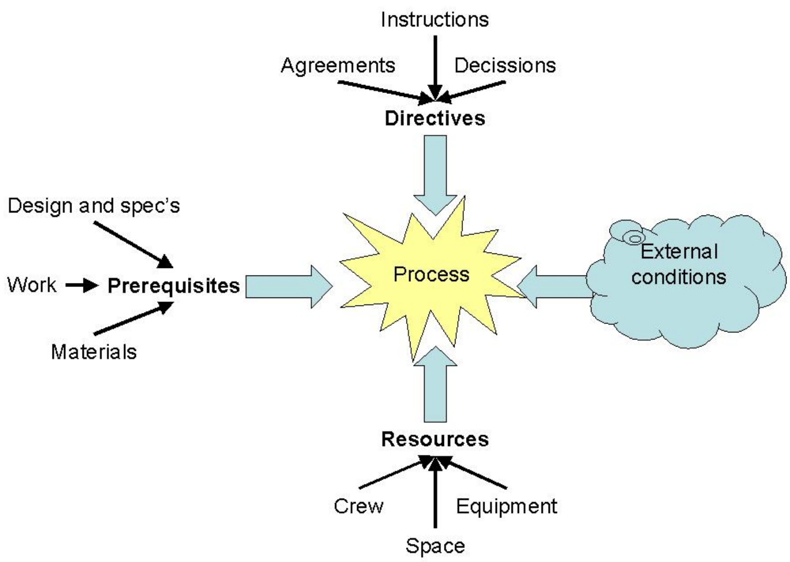

Figure 8: The 3 Type Model

Previous work is what we have at hand to work on just now, if the directives and resources required are available. It also expresses the state of the project albeit in an unusual form. Design may or may not be part of previous work depending on the type of contract – it may also be Directives; and Resources are the apparatus we have at hand to perform the job, which obviously comprises crew, equipment, space and often

– albeit not understood – the capacity of middle management (Kim and Jang, 2006). Interesting for this prerequisite is that Resources carry a limited capacity and that if not used at the moment available, this capacity is most often lost.

VARIABILITY IN THE CONSTRUCTION FLOWS

Any construction project is sharing its production system through the subcontractors' and designers' work on parallel projects, through the suppliers and through the equipment (Bertelsen, 2007). This means that variability in each of the flows exists but often due to circumstances outside the project management's control. Koskela (1999, 2000) showed that a 95 percent reliability on each of the seven kinds of flow in his model caused an only 70 percent reliability of the soundness of the activity itself, and Ballard and Arbulu (2004) in their presentation at IGLC 12 argued that this situation in practice may often be even worse, as the seven flows are seven categories of flows only, and that that the real number of preconditions for a sound activity might easily be much higher. They suggested app. fifty in many cases, in which case a 95 percent reliability causes a 8 percent reliability of the activity soundness and even just one percent uncertainty adds up to a 60 percent reliability only on the whole. As well Koskela (1999, 2000) as Ballard and Arbulu (2004) used the simple formula for adding up the impact of uncertainties, where all the certainties are the same:

$$\text{Certainty}_{\text{total}} = \text{Certainty} \uparrow \text{number of streams}$$ [10]

However, in real life things are not that easy because the various streams my have highly different reliabilities. The real way to asses the reliability should therefore rather be:

$$\text{Certainty}_{\text{total}} = C_1 * C_2 * C_3 \ldots .*C_n$$

where C express the certainty of each of the streams. An interesting aspect of this function seen from a management point of view is that there may be more than 7 flows and not least – no matter how few or how many – one bad apple will disturb the soundness of the whole, nearly independent of how high certainty is established in the remaining flows.

Looking at this in a wider perspective it must also be recognised that the flows themselves in many cases are not independent streams and that they are not only feeding the project in question. Most of the flows tie into other flows: The flow of design feeds the flow of materials and equipment, just as the flow of crew connect the projects to other projects through the trade contractors' management just as the design team may have several projects in progress, the materials supplier have a multitude of costumers and each of the trade contractors have several other projects to deal with – but with the same, limited amount of resources only. Foreseeing the critical flow is therefore not an easy task – if possible at all. But even though one can not see it, it is still there! And it is at the end of the day the critical flow that controls the progress of the project. So how do our tools for managing the project manage the critical flow?

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[10] A 5 percent uncertainty means a 95 percent certainty. With 7 streams the formula is thus $0.95^7 = 0.70$.

THE WORKING OF OUR PRESENT PROJECT MANAGEMENT TOOLS

Looking at construction from a flow perspective it is obvious that neither CPM nor the Gantt chart do much for the flow management. LOB does a little better as the flow of crews and space is dealt with to some extent but the variability in these streams are not considered just as flow of secondary space such as access lines, space for equipment such as cranes and scaffolding are almost not dealt with at all. As a planning tool LOB may therefore be better than CPM and Gant but not sufficient to really manage the flows.

Looking closer at these methods one recognizes that there are two underlying assumptions: That we know the sequence in which the activities should take place, and we know their duration. However, dealing with a flow system with an inherent variability this is not the case. Uncertainties in the flows influence the soundness of the work packages and thus their actual duration and this will often lead project management to change the sequence. The ordered model comes to a hold in managing the complex system.

More important than seeing the wrong assumptions on which the management tools are based is the question of what *should* be managed seen in the light of our new understanding of construction as a process fed by a number of flows. Obviously it is the flows themselves and not the operations as our management tools usually do. The point here is that managing the process in construction as seen from a process perspective may not at all be a task undertaken by planners with whatever planning tool they chose, but a social process This observation turns our attention to the Last Planner.

LAST PLANNER IN A PROCESS PERSPECTIVE

Last Planner has since its first introduction in the early 1990'es proved itself a useful tool in construction projects all over the world as reported at the annual IGLC meetings. However, even though Last Planner has been widely discussed there seems to have been speculated and reported very little on why it works so well. Our proposal is that – without saying so – the reason for the success may very well be that Last Planner through Look Ahead takes hand of all the flows and that the method turns planning into a social process in line with the complex nature of the construction process. (Bertelsen, 2003a; Bertelsen 2003b)

Managing the flows in construction does not take place as much at the weekly Last Planner meetings as at the Look Ahead sessions, where the external flows are dealt with. Internal flows such as release of work and thus flow of crew, as well as flow of space are still issues for the Last Planner meetings but they are rather a matter of negotiation and coordination than flow control as such.

Taking this approach, either Ballard's 3 prerequisites model or Koskela's 7 preconditions model come to mind. From a management point of view the 7 preconditions seem to be more practical. These seven flows can easily be made into check lists to be used at the Look Ahead meeting to make certain that work packages are made sound just as they may be used at the weekly work plan meeting to check the factual soundness. However, the 3 prerequisites may form a framework for the coordination.

No matter which model is used, flow reliability should be in focus in management activities. PPC[11] has with great success been used on the reliability of the weekly work plan but it is here suggested that PPC is used in any activity which includes a number of commitments, i.e. the Look Ahead planning, the design meetings etc.[12]

Understanding the construction process from a flow perspective may really change our understanding of the nature of project management. Resent Danish experience indicates that the crews themselves by their crew leaders are quite capable of running the weekly work plan meeting once they understand the nature of the process (BygSoL, 2007). To avoid conflicts a Process Manager has been introduced to conduct the planning meetings and to take hand of failures in the flows, often observed through PPC (Bertelsen and Koskela, 2002). This releases to a great extent the superintendents from the planning of operations and makes more room for managing the flows through the Look Ahead process. The Phase Schedule becomes thereby the overall mapping of the desired process and an instrument for reporting where the process is, compared to where it should be, but not at all an instrument for conducting the work.

Indeed, this new understanding has made the first author to put forward the question whether we need a project management for the operations at all, and not just one in order to coordinate the Phase Schedule and to make sure, the Look Ahead process works.

CONCLUSION

The process understanding of construction presented above seems to have the potential for a new understanding of project management and its tools. Even though a management by critical flow sounds tempting the problem may easily be that the critical flow is hard to identify and may change from day to day or even from hour to hour. The challenge is therefore rather to develop tools for managing the flows, not least the flow of information, crew, materials, space and equipment.

IGLC has over the years presented a number of papers on these issues and it seems to be a valid undertaking to gather these reports and to put them into a system for managing flow in construction, which may easily take focus away from the tools for managing the operations.

Indeed, we have reason to believe that with a good social system on the site combined with a diligent management of the flows in order to ensure the just-in-time reliability, the operations may almost manage themselves.

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[11] PPC: Percent Planned Completed; Ballard (2000)

[12] Doing this at the project management level in a major Danish project showed initially a PPC as low as 20 percent, which rose to over 80 percent over a few weeks after the introduction of the procedure.

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