CRITICAL FLOW – TOWARDS A CONSTRUCTION FLOW THEORY

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ABSTRACT

This paper introduces the concept of *Construction Physics* as a more comprehensive way of understanding the construction process from a flow perspective. It establishes a preliminary definition of the term and investigates briefly the present knowledge, flow models and methods for their management. From this it argues that the state of the art does not fully cover the whole process and proposes a holistic view of the flow of all prerequisites feeding the process. It introduces the key term Critical Flow and concludes by recommending areas that should be investigated as a joint IGLC research, development and testing programme.

KEY WORDS

Critical flow, construction physics, flow management, theory, variability.

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INTRODUCTION

This paper addresses a proposal to the IGLC community: to put together the large number of contributions on construction flow presented since the first meeting in 1993 to create a flow model of the construction process and thereby reach a deeper understanding of its nature - a Construction Physics.

In doing so the paper in itself does not present substantial new research. Instead, it presents new conceptual insights, thus it should be seen as a research proposal to the IGLC. In the spirit of IGLC, the authors are not in total agreement on all the details.

Background

Since the foundation of the IGLC researchers have seen the construction process as a flow of work delivering value to the client (Ballard 1993; Koskela 1993). Over the years this understanding has grown in importance and its usefulness in a number of cases has been reported along with detailed studies of some of the flows. In the same period a general theory for the construction process has been developed (Koskela 2000) along with Last Planner as a tool for managing the flow of work.

However, most of this research has been focused on the flow of work, i.e. logical sequence of tasks. Even though some have studied the flow of materials and components, the remaining flows that also feed the process (e.g. flow of crew, information or equipment) have been dealt with sparsely. Therefore we feel that the time may have come to establish a more general flow model which takes into consideration the nature of all the flows in a construction process and their respective interactions.

Another fact that stresses the need for a common understanding of the flow principles is the misinterpretation and dissemination of these concepts by authors outside the IGLC community. As an example of this mismatch we have the debate between Thomas et al. and Ballard et al. in an article regarding labour variability in the Journal of Construction Engineering and Management (2003).

Objective

Briefly, it can be stated that the objectives of the proposed study are:

- Delivery of prior works – putting our knowledge together in a more general context;
- Opening of new lines of thinking – based on the theory developed within IGLC;
- Establishment of a general flow model for the construction process and analysis of the nature of the flows;
- Setting out of a research agenda;
- Critical analysis and evaluation of the suitability of the flow management tools and principles used in construction management;
- Proposed improvement to existing tools and development and testing of new ones.

Paper structure

The paper sets out by establishing a definition of Construction Physics. It then proceeds by outlining some of our knowledge and understanding of flows in construction, and it looks briefly into approaches to encountering the variability in these flows. It proceeds by examining some of the prevailing methods for the control of flows and recognizes that none of them are able to deal with them all in a systematic way. Finally, it proposes some areas where a deeper study into the nature of the flows would be beneficial; from a comprehensive review of our present knowledge to the development of new methods and tools for flow management.

As the paper mainly addresses the IGLC community, most of the background knowledge is assumed and only key contributions are referred to.

WHAT DO WE MEAN BY CONSTRUCTION PHYSICS?

The philosopher Karl Popper (1978) suggests that we can distinguish three different, though interacting, worlds: an objective physical world; a subjective mental or psychological world; and a world of human creations, which although its significant features are non-physical is also objective. This ontological schema proves useful in understanding the nature of construction flows. The physical world, or World 1, is represented in the flow of plant, materials, work teams, etc. World 2, the psychological, is significant for subjective human resource issues, particularly commitment. Works information, design and the production system itself, however, are World 3 phenomena, although a product of the human mind, they nevertheless have an objective existence. Construction physics deals with World 1 and World 3 phenomena. Which of course raises the question how do these phenomena interface with World 2, or whether indeed the mental and physical can be analytically separated in a feasible way?

However, that we have defined our focus as construction physics, does not yet fix the metaphysical commitment to be made. As explained in (Koskela and Kagioglou 2005), the tension between two metaphysical stands, on the one hand, thing ontology, and on the other hand, process ontology, has existed from the very beginning of philosophical and scientific pursuits. It is prudent to assume that different situations require different ontologies. We explore here the possibility that construction is best served by process metaphysics.

Flow in Construction

Construction Physics is a theory based understanding of the nature of the flows and their interactions in the construction process. The flows comprise physical flows in the traditional sense, such as flow of materials and equipment, but also immaterial flows such as flow of information, crew, space and external conditions (weather, authorities' approvals, etc.). In short: Construction Physics deals with the flow of all the prerequisites, which make the process sound and it consider as an outset these flows as equally important for the soundness of the process[5]. Construction Physics also looks at the interaction between the flows such as how the flow of materials influences the flow of space.

[5] By a sound process we understand a process where all prerequisites are in place and where the operation can be performed without any delay.

In doing so it aims to identify and act in the flow – or combination of flows – which contains slow rates of productivity, discontinuity, constraints, and bottlenecks for the whole process: flows that we call the *Critical Flow.*

Construction Physics has the construction process as its focus point. Thus construction is not understood as a chain of discrete activities; instead Construction Physics considers construction as a continuous process being fed by a number of streams, where the content of these streams decides the actual outcome.

Construction Physics has one basis in queuing theory and is thus inspired by Factory Physics (Hopp and Spearman 2001). The doctrine of Factory Physics contends that by means of queuing theory, various insights, which have been used as heuristics in the framework of JIT, can be mathematically proven. In totality, 15 laws on the behaviour of production flow lines are presented. Maybe the most fundamental result regarding production control is that in view of a certain level of variability in production, there is always a penalty in one form or another, even if the control is the best possible.

However, where Factory Physics looks at the flow of parts only, Construction Physics takes a broader approach by looking at the production process as a whole and also by adapting the ideas of Factory Physics to the context of construction. Particularly, we contend that the following issues require attention:

- One may argue that Factory Physics and similar approaches, such as the seminal work by (Gilbreth and Gilbreth 1922) – and in modern time the work of Goldratt (1997) – all have an underlying 'Matter metaphysics', Construction Physics is based on a 'Process metaphysics' (Koskela and Kagioglou 2005). For example, the phenomenon of making-do can adequately be understood only through process metaphysics.
- In construction, there is one single, large intermediate product, onto which parts are assembled by mobile work stations. Thus, the scheme of factory physics, depicting parts traversing through a network of workstations, has to be modified.
- Many issues that can be abstracted away in Factory Physics, or can be assumed to be constant, have to be explicitly modelled regarding their variability in Construction Physics.

CONTEXTUALIZING CRITICAL FLOW MANAGEMENT

Looking at the construction process from a flow perspective is not something new. Indeed, it can be seen as one of the most important issues dealt with by IGLC since the very first meeting in 1993. This perspective has over the years led to development of the T-F-V theory (Koskela 2000) as well as new management tools (Ballard 2000) and to new management principles (Bertelsen and Koskela 2002).

Over the years several studies on some of the flows have been conducted by contributors such as Tommelein, Sacks, Ballard, Howell, etc., and some ideas of the kind and the nature of the process prerequisites have been put forward. However, a general, comprehensive and in depth study has never been presented.

Which are the Flows?

Anybody having encountered the construction process will know that there is a plethora of flows feeding the process. Some are easily identified such as the flow of materials, while other is more tacit assumed such as tools. Some are material while other is immaterial such as flow of information, directives, approvals and the weather. But all are mandatory for the sound process.

Koskela (2000) identifies seven types of preconditions for the sound process:

- Construction design
- Components and materials
- Workers
- Equipment
- Space
- Connecting Works
- External conditions

Even though this concept of seven flows has been successfully used as an instrument in the Danish understanding and implementation of Lean Construction, one may argue that it is not based on a structured analysis of the nature of the process and its flows.[6]

However, Koskela (2000) also presents a three type flow model which identifies:

- Materials
- Location (space)
- Assembly (previous work)

The model is presented as a comparison between car manufacturing and construction and not as a general model for the construction process, which may explain that important flows (in construction) such as information, crew, and the weather are not included.

Ballard (1999) presents a more general three flow model based on the nature of the flows:

- Directives
- Prerequisite work
- Resources

> "*Directives provide guidance according to which output is to be produced or assessed. Examples are assignments, design criteria, and specifications. Prerequisite 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)*

[6] Indeed, they are just put forward as an example of the impact of a relatively small uncertainty in each of the flows on the soundness of the whole process. Koskela shows that 5 percent uncertainty on each precondition leads to 30 percent uncertainty on the totality. And as this is one of the inflows to the upcoming process the uncertainty will inevitably grow.

This is probably the most general model of flows but it is obviously not directly suited for management, i.e. flow of prerequisites includes procurement along with flow of work, etc. If it is going to be used in the further work, each of the underlying flows as defined by Koskela's seven prerequisites flows should probably be used as sub-flows.

Encountering the variability

Given that in Factory Physics, the primary explanation of performance is the level of variability, it is obviously paramount to manage production well from this angle. There are three distinct, but interrelated ways of encountering variability in the production system: at the level of production system, control or improvement (Koskela 2000).

The most basic solution to these problems is at the level of system design. The basic goal is to avoid features in the production system design with high inherent variability or which are amplifying variability. Site problems can be alleviated by configuring the production system so that a minimum number of activities are carried out on site. The rationale of prefabrication, modularization and pre-assembly is partly based on this principle. The problems stemming from one-of-a-kind features can be alleviated by using standard parts, and pre-designed solutions, etc. Interference between flows and tasks can be reduced through procurement strategies such as the French sequential procedure, where there is always only one company working on site. Logistical variability can be reduced through an off-site central warehouse. Multi-skilled teams provide flexibility to encounter small-scale variability in the work flow.

The next option is to mitigate inherent variability in the level of control. There are three requirements to be set for optimal control. First, we want to avoid the cascade of point wise deviations to other tasks, i.e. variability propagation (Lindau and Lumsden 1995). Of course, the same applies for self-infliction of variability by control. Secondly, we want to avoid unnecessary penalties for variability. As discussed above, regarding production control for a given variability level, there are three optional penalties: buffering of flows, lower utilization of resources or lost production (due to starvation or, particularly in construction, due to suboptimal conditions) (Hopp & Spearman 2001). Thirdly, out of the necessary penalties, those should be selected that minimize the disadvantages in view of overall objectives. Without going into details, methods available at this level include: buffering; batch size selection; capacity adjusting; pushing/pulling. In addition, solutions which go beyond the Construction Physics framework may prove crucial for stemming inflow and process variability: for example, decision rules that demand that only sound tasks are started (for eliminating making-do) and structured conversations for ensuring the commitment to realize each task as planned.

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 succeeded. Theoretically, the question is about the scientific experimentation model of (Shewhart and Deming 1939). The method of Last Planner is instrumental for these purposes: it effectively combines control and improvement to fight back against variability and the waste caused by it. However, it is also otherwise possible to aim at increased reliability of deliveries and added conformance to schedule in collaboration with all parties.

PRESENT STATE – WHAT DO WE KNOW?

A brief look through contributions to the last nine IGLC conferences as reported in (Bertelsen, 1999 … 2006) shows that that individual flows have been studied in quite some detail but the totality has seldom been approached in anything more than general terms (Ballard, 1993). The survey also revels that we have a lot of empirical results but very little theory. Deeper studies of the nature of the flows – besides some computer simulations – are almost non-existing.

Planning and Control: Tools and principles:

Looking at some relevant production management methods it is easily observed that there is not a current method able to manage satisfactory all the seven precondition flows. What construction managers have been doing is trying to allocate the most suitable method to a specific situation according with the project stage (see Table 1). The Critical Path Method (CPM) is very useful in the project early stages, where it is needed to decide the logical sequence of works, project cost forecast, milestones, and total project duration. CPM has been used in construction more as a strategic decisions and contract management tool. Its applicability in intermediate terms is questionable, because it does not show in what way to execute and control activities, and it is also difficult to keep up-to-date.

Table 1: Project length and current production management methods and techniques – Generic overview

<table>
<tr><td>Decision level</td><td colspan="3">Strategy</td><td colspan="2">Tactics</td><td colspan="2">Control</td></tr>
<tr><td>Time Horizon</td><td colspan="3">Long term
(Year)</td><td colspan="2">Intermediate term
(Month)</td><td colspan="2">Short term
(Week)</td></tr>
<tr><td>Planning</td><td colspan="3">Master</td><td colspan="2">Look-ahead</td><td colspan="2">Weekly</td></tr>
<tr><td>Method interfaces</td><td colspan="2">CPM</td><td colspan="2">LOB</td><td colspan="2">Critical Chain</td><td>Last Planner System</td></tr>
<tr><td>Technique interface</td><td colspan="4">PUSH</td><td colspan="3">PULL</td></tr>
</table>

Another less widely diffused approach is Line-of-balance (LOB) that proposes to manage the flow of space. Although it still assumes a linear flow of work, it provides easy visual management and levelling of production rhythms. A criticism of LOB is that it has management limitations on complex and non-repetitive projects (Henrich et al. 2005).

A project is not an isolated production process; it often shares its (human, information generation and equipment) resources with other projects. Goldratt (1997) recognizes this and deals with the problem of sharing human resources over different projects, albeit within the same organization, meaning that allocation of resources to projects can be based on an overall optimization of the enterprise. This approach is called Critical Chain, and contrasts with the CPM idea, that tends to assume the management of an isolated project with unlimited resources.[7]

Last Planner™ has been shown to be an effective tool for dealing, not only with variability, but also with unforeseeable issues as well. It deals with a chaotic situation by establishing a

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[7] Critical Chain is not about the shared resources only but also – and maybe more important – about managing time-buffers, which should be kept in mind when we reach the development of management principle phase.

pull logistic and changing the work sequence by commissioning work made ready, and not only managing buffers.

Table 2 presents the capacity of some relevant current production management methods in managing the 7 precondition flows. What this table suggests is that construction demands another approach to deal with Construction Physics, mainly in the intermediate term, where the Last Planner System does not cover it completely. Furthermore, thereby Last Planner takes into consideration all the flows of prerequisites even though it does so mostly indirectly and it does not present general tools for the management of the remaining six flows. And their nature is not dealt with in detail either.[8]

Table 2: Preconditions and Production Management Methods in Construction –Generic overview

	Previous Work	Space	Crews	Materials	Equipment	Information	External Conditions
CPM	x				x		
LOB	x	x					
C. Chain	x		x		x		
LPS	x	x	x	x	x	x	

In the early 1990's some experiments on just-in-time logistics were carried out in Denmark under the Heading: *Building Logistics.* The general idea was to ship materials to the site as kit packages compiled for the operation in question and using the materials whole sale dealers as repacking centres and de-coupling points (Bertelsen (1993, 1994), Bertelsen and Nielsen 1997). The control system developed for this flow was at the outset very similar to Last Planner but unfortunately without an underlying theory of the nature of the construction process. While the first two tests were a great success, later tests showed a declining rate of improvement until the seventh trial actually recorded a lower level of productivity and the experiment consequently abandoned (Clausen 1995, Clausen and Nielsen 1996).

At the same time, studies into the flow of information have been conducted in the light of the new information technology that is increasingly used in the design process (FRI 1989, Bertelsen 1992). Even though there seemed to be a large productivity improvement to be gained through this approach, very little has been done since. Could this be because the effort must be made by the designers whereas the benefits accrue to the contractors?

FUTURE STATE – WHAT DO WE HAVE TO DO?

Looking at the state of the art from a holistic flow perspective shows that even though our present knowledge is in most cases better than that which is exercised in practice, still some (if not all) flows need to be investigated in more detail and management methods to be scrutinized in the light of the new understanding. The general success of Last Planner is a strong argument for this statement and the success of the few experiments in material management also support it.

8 This is not said to criticize Last Planner, which has shown its value over and over again in practice but only to express that there are room for an even deeper understanding of the construction process from a flow perspective.

This work should establish the basis for more comprehensive studies of the interaction between flows, aiming at developing better methods, tools and principles for their management. This will obviously bring Popper's World 3 into our thinking, as we well recognize (Buch and Sander 2005; Macomber and Howell 2003), but the important issue is to understand the 'nature of the beast' before we try to understand how to control it.

Future research should thus cover issues such as:

- Establishing a more comprehensive understanding of the nature of each of the flows;
- Revisiting previous (IGLC) work and gathering it in a bibliography;
- Supplementing this by studies of the remaining flows and outside work;
- Studying the interaction between flows to develop models and simulations
- Investigation of present tools with regard to the nature of the flows;
- Improvement, development and testing of management tools.

The outcome should be:

- A deeper understanding of the nature of flows in the construction process;
- A framework for production management;
- Facilitation of learning;
- Better tools for process design and control;
- Less waste;
- Better projects.

CONCLUSION

The work performed within this project up till now has shown us that there is a need for a deeper understanding of the construction process based upon true process metaphysics. This new understanding may lead us to flow models better suited as a basis for project management and at the end give rise to a better performance of the construction industry.

It is proposed that IGLC discuss such a joint research project, which may serve two purposes: generating a deeper and more general common understanding of the process; and furthering cooperation in the periods between the annual meetings.

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