CONCEPTUALIZATION OF INTERDEPENDENCY AND COORDINATION BETWEEN CONSTRUCTION TASKS

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ABSTRACT

We address the understanding of coordination in construction by applying a theoretically informed case study approach. The main theoretical resource is coordination theory based on dependence structures between resources and activities. Empirical data from different typical construction projects are applied. The critical path method is not an adequate answer to the coordination of reciprocal interdependency in construction work, and our empirical observations confirm that in such cases planning and production are two different worlds rather than integrated activities. We offer theoretical arguments for coordination through mutual adjustment in construction production. The Last Planner System can potentially extend the benefit of planning and enable better control of the fine-grained make-ready process for production, but its shortcomings in the time-frame between Last Planner meetings have required additional practical coordination effort, which up to now has been based on the language action perspective.

KEY WORDS

Coordination theory, interdependence, production planning, Last Planner System.

INTRODUCTION

Coordination is a central management task. In lean construction, it is among the key achievements of the Last Planner System (LPS), whose primary concern is to coordinate resources and decisions aimed at creating production predictability, in order to reduce the level of waste through reduced variability. Ballard (2000) describes LPS as "work flow control" which means to coordinate the flow of design, supply, and installation *through* production units. Production predictability is also a central concern within project management (e.g. Winch 2002), and supply chain management (SCM) (e.g. O'Brien *et al.* 2009; Prike 2009).

The Last Planner System can be regarded as an empirically-based normative system which has often turned out to function better in practice than the more traditional forms of production planning (Ballard and Howell 2004). Many researchers have sought theoretical explanations for the success of the LPS. In this context, Macomber et al. (2005) and Macomber and Howell (2003) introduced the linguistic (or language) action perspective as a contribution to the theory of lean construction. The language action perspective includes a strong focus on

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coordination, as we shall see below. Isatto and Formoso (2009) also address language action theory and coordination theory in their discussion of supply chain management in construction, which is related to the LPS. They base their coordination theory especially on Crowstone (1991), who in turn builds his theory on the works of March and Simon (1958) and Thompson (1967 and 2003). Crowstone introduced the notion of "flow dependencies" and dependency related to the use or creation of common resources. Sacks and Harel (2006) used economic game theory to show how the LPS can influence managers' and subcontractors' behaviour. They demonstrated that subcontractors are more likely to allocate their resources to projects that have stable planning than to projects where the progress of work is unpredictable, moving away from the opportunism that keeps them in stable lose-lose equilibrium states and toward theoretically less stable states that require a degree of collaboration, but result in higher utility for all concerned.

In this paper, our primary aim is to contribute to a theoretical understanding of dependencies between tasks in construction – dependencies which in the next instance call for coordination. We examine basic coordination as a management activity that arises from the need to handle dependencies between multiple activities (Thompson 1967/2003; Malone and Crowstone 1994). Our main focus, then, is on the technological properties of different kinds of work which create the need for different forms of coordination. The basic proposition is that if practitioners know these underlying properties, they can rationally differentiate the resources applied to coordination, including organisational measures. At a somewhat deeper level, we may say that dependencies arise from specialisation and the division of labour, as evident between the architect, various engineering disciplines, and the different trades involved in modern construction. In addition to these factors, different relationships and power structures connected to responsibilities and roles/contract strategies between the client, main contractor, subcontractors, suppliers, architect, and engineers are also involved. Our secondary research aim is to relate the theoretical clarification to the LPS with a view to strengthening the system's theoretical foundation.

With respect to coordination theory, we have mainly chosen to seek support in the work of Thompson (1967/2003), which sheds light on dependencies as underlying factors for coordination. Thompson's work is presented below, as is the language action perspective – with a comparison between the two, and a discussion of their respective merits. This is followed by an analysis of a series of examples related to coordination theory based on dependencies, and a discussion of the Last Planner system according to the same theoretical perspective. Finally, conclusions are offered.

THEORY OF COORDINATION

Different types of interdependencies call for different modes of coordination. Thompson (1967/2003) focuses on internal interdependency in complex organisations. However, we have chosen to take a wider view which includes interdependency between activities in the same organisation as well as between different organisations; see for example Kalsaas (2011).

Thompson proposes three types of internal interdependence, namely pooled, sequential and reciprocal interdependence related to his conceptualization of different technologies in organizations. His point is that different technologies characterized by differences in interdependence call for different management measures and modes of coordination. The technical parts of an organization system are seen by Thompson to provide a major orientation for the social structure, and it appears that if we wish to understand organizational structure, we must consider what is meant by interdependence and what is meant by coordination, and we must consider various types of these. By building upon Parsons (1960) he operates with the technical, managerial, and institutional level, and postulates that every organisation strives to achieve effective performance of the technical function, while the managerial function mediates between the technical sub organisation and the customers (users of output) and procures the resources necessary for carrying out the technical functions. Institutions are the wider social system including regulation from public authorities. Because these three levels are interdependent, differences in technical functions should correspond with differences at the managerial and institutional levels of an organization. Therefore technology is important for understanding the actions of complex organizations, Thompson argues.

Pooled interdependence is the type of interdependence we can find between the head office and branch plants where the branches may not interact at all (although they may be interdependent in the sense that unless each performs adequately, the total organization is jeopardized). **Sequential interdependence** is a pattern of direct interdependence where K must act properly before T can act; and unless T acts, K cannot solve its output problem. The third form is called **reciprocal interdependence**, and it refers to a situation in which the outputs of each become inputs for the others. Airlines, for example, have both maintenance and operations units. The production of the maintenance unit is input for the operations unit, in the form of serviceable aircraft; and the product of operations is input for maintenance, in the form of aircraft needing maintenance. There is a pooled aspect to this, and there is a sequential aspect since the aircraft in question is used by one, then by the other, and again by the first. But the distinguishing aspect is the reciprocity of the interdependence, with each unit posing contingency for the other. All organizations have pooled interdependence; more complex organisations have sequential as well as pooled interdependence; and the most complex have reciprocal, sequential and pooled interdependence. The three types of interdependence are increasingly difficult to coordinate because they contain increasing degrees of contingency, which also mean increasing cost to coordinate.

In a situation of interdependence, concerted actions come about through coordination. Where there are different types of interdependence we would expect to find different devices for achieving coordination. Thompson addresses coordination by **standardization**, by **plan** and by **mutual adjustment** (coordination by feedback). Coordination by standardisation involves the establishment of routines or rules which constrain the actions of each unit or guide their actions into paths consistent with those taken by others in the interdependent relationship. Coordination by plan involves the establishment of schedules for the interdependent units by which their actions may then be governed. Coordination by plan does not require the same degree of stability and routinisation that is required for coordination by standardization. Coordination by mutual adjustment involves the transmission of new information during the process of action. Coordination by mutual adjustment may involve communication across hierarchical lines, but it cannot be assumed that it necessarily does so. The more unpredictable and subject to variation the situation, the greater the reliance on coordination by mutual adjustment. The three types of coordination, in the order introduced, place increasingly heavy burdens on communication and decision-making. Standardization requires less frequent decisions and a smaller volume of communication during a specific period of operations than does planning, and planning calls for less decision and communication activity compared to mutual adjustment. Coordination by plan is associated with “long linked technology” and coordination by mutual adjustment is associated with “intensive technology”.

COORDINATION UNDERSTOOD AS LANGUAGE ACTION

Macomber and Howell (2003) base their application of the language action perspective (LAP) on Flores’s (1982) work. Flores states that “*the work of business is making and keeping commitments*”. This understanding is contrasted with activity-centred project management, which the authors associate with the Critical Path Method. The LAP is related to an interpretative structure for explaining and acting in a number of domains, the most basic of which is the “*everyday coordination in action*”. In short, this theoretical understanding builds on the existence of commitments between the different actors and trades involved in construction projects. Commitment loops are generally about communication between a requirer (customer) and a performer, and span the stages of request, negotiation, performance, and satisfaction (Denning and Medina-Mora 1995). Grandori (1997) also sees communication as a coordinating activity. From this perspective, “*projects are promises to the client and their completion is realized by action coordinated through promising at every level*”, according to Macomber and Howell (2003).

Macomber et al. (2005) follow up on the managing of promises with the LPS, and home in on uninterrupted flows. They address the fact that we cannot keep all our promises, and point to the need for regular re-promising at the task level of projects, as the future is uncertain and unknowable. Furthermore, they identify a need for Daily Promise management meetings (stand-up meetings).

CLOSING IN ON COORDINATION THEORY

The LAP is a positive contribution in terms of understanding the LPS and what it takes to make it work better. It endorses dialogue and adaptation in order to remove obstacles, exchange information about completed tasks and specific issues to look out for, and so on, to ensure the best possible flow of work involving different trades and actors. The LAP inspired stand-up meetings can be understood as mutual adaptation in the sense describe by Thompson. However, Thompson’s coordination theory is founded on analysis of technological dependencies which are at the basis of different modes of coordination. Macomber et al. (2005) touch upon dependencies in their statement that "dependence is the norm in the project environment" (p. 16), and hint at dependency based coordination theory when they suggest that the function of the Daily Promise Management Meeting, as an extension of the LPS, is to provide a forum for "mutual adjustment". They do not, however, conceptualise the notion nor do they provide a differentiated understanding of dependencies. A study of dependency structures between the tasks involved in work packages can yield a differentiated answer to what measures of coordination are most likely to optimise results, thus making it a more useful theory than the LAP for guiding actions.

Seen in the light of coordination theory, it is obvious that having stand-up meetings on a daily basis works better than not having such meetings, because it introduces the principle of broad mutual adjustment on a daily rather than a weekly basis. But even on the day-to-day level promises can fall through, and measures other than the agreed ones may be required in order to best handle the situation because of the interwovenness of some tasks with their reciprocal dependencies. On the other hand, the mutual adaptation requirement can be somewhat relaxed for work packages dominated by sequential dependencies.

Furthermore, an understanding of different types of dependencies will help inform management decisions in terms of how to divide the work between companies and actors in such a way that the most complicated dependencies are avoided, or entered into with open eyes. It is not a matter of the technology being determinant, in other words. Management level decisions about division of labour are also of significance.

RECIPROCAL INTERDEPENDENCE IN SITE PRODUCTION

A simple example of reciprocal interdependence is when a carpenter puts up a non-loadbearing wall inside a building. The normal procedure is that he will put up the frame, mount the drywall on one side, and put in the heat insulation. Then the plumber and electrician mount their pipes and conduits, before the carpenter mounts the drywall on the remaining side. The next step is often that the painter arrives and finishes his job, before the plumber and electrician return to complete their systems. In this example, there is reciprocal interdependence between the carpenter and the plumber, and between the carpenter and the electrician. If everything that needs to be mounted inside the wall is not in place when the carpenter seals the second side, or if the design is subsequently changed, a great deal of unnecessary work and waste can easily ensue. It is generally assumed that the best insurance against future problems is that the carpenter, plumber and electrician jointly inspect the installation before the wall is sealed – i.e. coordination through mutual adaptation. From a work flow point of view, this pattern of trades returning to the same space multiple times has been identified as 're-entrant flow' (Brodetskaia*et al.* 2010). Re-entrant flow has broad implications for the allocation of resources because it unbalances production systems.

Figure 1 illustrates a more complex example of reciprocal interdependence involving a larger number of factors. In the Havlimyra project in Norway (Kalsaas et al. 2009; 2010), the designed building (a nursery school/kindergarten, school, cultural centre) was designed to have a centrally controlled heating system based on waterborne heat, with geothermal energy provided through a heat pump and delivered by recycling of the exchanged indoor air. The room climate regulation is based on the CO^2 content and temperature monitored in each room. Five trades are included in the figure: PM ventilation, PLC automation, ventilation technology, electrical and electronics engineering, plumbing and hydraulic engineering. For sake of simplification, we have excluded the structural engineering consultant, the tinsmith who installed all the ventilation ducts and variable air volume (VAV) terminal units and various other trades (carpentry, fire insulation, painting and flooring).

The figure illustrates that the installation of the ventilation system involves a series of interdependences, both reciprocal and sequential. For example, the plumber delivers pumps for the system, and pump data is used for the automation engineering and the electrician's circuit diagrams of the sensors involved. Furthermore, the plumber integrates shunt valves, temperature sensors and a series of pumps into the piping system based on automation engineering data. The plumber's balancing of water and air temperatures as well as the electrician's wiring and installation of sensors and electricity supply must be in place before the VAV part of the installation can be adjusted, and the final PLC programming performed. In the final calibration phase it is absolutely necessary that the programmer and the ventilation technician are simultaneously present. Furthermore, it is highly desirable that the electrician also be available for potential adjustments or corrections of sensors and other factors.

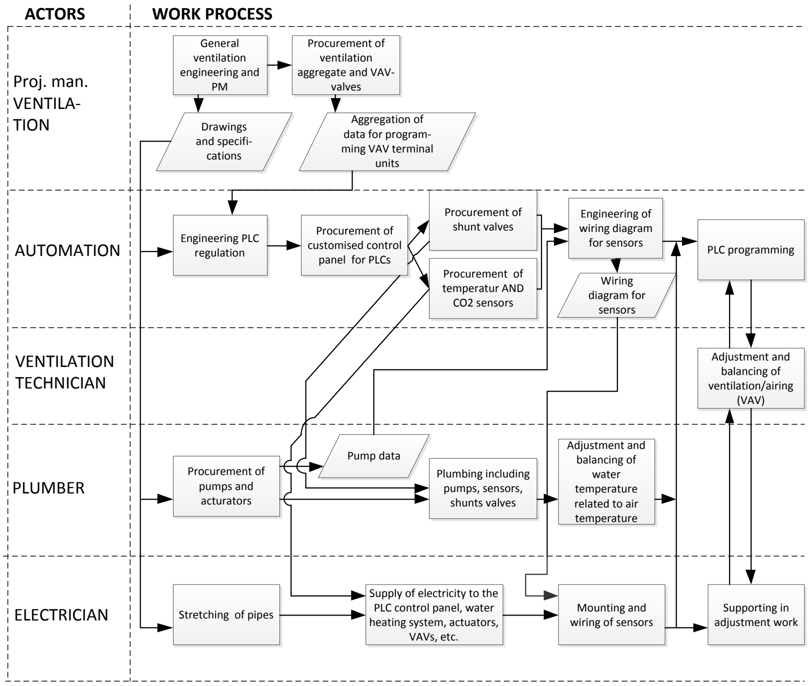

Figure 1. Reciprocal interdependence observed in the Havlimyra project, Norway.

COORDINATION BY MUTUAL ADJUSTMENT IN CONSTRUCTION

To achieve smooth workflows where reciprocal interdependence exists requires mutual adjustment. The following anecdotal cases illustrate this point, with both failures and successes.

In the Havlimyra project, construction of the ventilation system gave rise to a series of problems. Automation handed over the wrong circuit diagram, too late, to the electrician – who, as a result, had to pull cables through finished walls to right the error. The plumber had to wait for delivery of shunts. Furthermore, ordering of the control panel was delayed because the builder was late in deciding what heating system to opt for; with better communication, the control panel could have been ordered earlier. These are examples of the contingency the different actors impose on each other. Coordinating tasks such as these through a plan is difficult, if not impossible, and any such plan must be supplemented with coordination through mutual adjustment in order to ensure good work flow. Planning inspired by Last Planner was used in this project, but for this particular sub-process, the positive effect was limited.

In another Norwegian small-to-medium construction project (Odderhei) a young project manager was in charge. In line with standard practice in the general contracting company, and according to what he had learned in his engineering training, he applied a Gantt commercial software package to indicate work tasks at a fairly detailed level (master production plan). Data indicates (Gundersen and Fønstelien 2008), however, that the experienced trade crews paid little attention to the master plan when they made their weekly work plans and partly decided what to do on a daily basis. These two plan types appear to have independent lives. The work flow appears to have gone well in the project, probably because the experienced crews applied mutual coordination on site with other trades in their daily work. The rather successful result might also be attributed in part to the generous contractual throughput time set for the production phase. This illustrates that increased time compression can be expected to increase the challenges involved in the coordination work. Another student project (Hermann 2011) shows that the respondents in a renovation project agreed that what was needed in order to improve workflow – which included increasing the proportion of direct work – was better planning. There does not seem to be any widespread deep understanding that planning as a coordination method has its limitations. In addition, renovation projects can be expected to require more mutual adjustments than new build, due to the great uncertainty involved when intervening with old structures.

The discrepancy between 'bureaucratic' master planning and the realities of day to day task execution in construction as described in this case appears to be typical of the majority of traditionally managed construction projects throughout the world. Indeed, Applebaum (1982) provided an excellent early description of the phenomenon. In the case study reported, the discrepancy resulted from the management's misconception of the work as being sequentially interdependent when in fact it is reciprocally interdependent. The managers assumed they could use coordination by plan, when mutual adjustment was in fact needed.

Late delivery of steel roof trusses at the Havlimyra project (ibid), which the fabricator explained by lack of steel deliveries from his supplier, caused delay in the carpenters' preparation for roof covering. When the preceding work was delayed for two weeks, the roofing subcontractor was not able to start directly as he was busy with another project, and the roof was delayed another week and a half. When a trade is delayed or does not show up, or material or equipment is not delivered in due time, it results in a situation where each trade imposes contingency for the other, not least when the progress is on the critical path and there is no or very little slack. Even though the work is dominated by sequential interdependency as in the described example, there is in fact a reciprocal interdependency related to the other projects many of the subcontractors are involved in. This interpretation is supported by Bertelsen and Sacks (2007) description of the reciprocal nature of the constraints imposed on the availability of labour by subcontractors' concurrent commitments to multiple projects.

Observations made in the course of the KanBIM research (Sacks et al. 2010) on a large construction project in Israel (four 20 story apartment towers with a total of 288 apartments) provided insight into traditional production management practice. The general contractor's policy was to carefully plan the weekly work for the trade crews according to a desired production rate of one floor (four apartments) per week per operation, and then to demand this rate from the subcontractors. The plan considered the work to be essentially sequentially interdependent, although it did recognize the fact that some trades and tasks were reciprocally interdependent, with the consequent need for additional trade crews when a particular trade was required to work on more than one floor at a time. In practice, the site supervisor's attempts to coordinate between the trades using coordination by plan were largely ineffective. Trade crews added and withdrew crews according to their own priorities (such as demand from other sites), essential materials were often found to be unavailable, and the variations introduced by client-driven design changes led to low values of percent plan complete (PPC). However, the trade crews did not practice coordination by adjustment, as might have been expected given the reciprocal nature of the interdependence. Instead, they preferred to allow large buffers of work-in-process to accumulate between each trade, so that they could perform work once it become visibly and demonstrably mature. In this way they did not need to coordinate explicitly with other crews. Work thus progressed in what can be termed an 'emergent' fashion – work was done as it became ready, without an explicitly managed or predictable make-ready process.

An empirical example of mutual adjustment can be found in Cuperus et al. (2010). The project involved the construction of 82 terraced housing units, and many of the customers had made individual choices in terms of materials and equipment. The average fit-out time was 35 days. Two of the units were picked for a trial experiment of using multiple-trade teams across sub-contractor boundaries, inspired by the Last Planner System. Completion of the trial units was planned to take 10 work days. The time it actually took to complete the units was 11 days and 19 days, respectively. The experiments in the example were not guided by theory, however, and also indicates the correctness of our assumption based on general empirical observations that experienced construction workers know to a great extent what will work in practice, and that they call meetings and conduct on-site inspections to resolve stuck situations (fire fighting). Our point here is that if guided by theory, we can increase the accuracy of the implemented measures by differentiating the coordination according to the need – as put by Lewin (1958), "there is nothing so practical as a good theory".

LAST PLANNER SYSTEM AND COORDINATION THEORY

The Last Planner System (LPS) (Ballard 2000) is a practical approach in which construction managers and team leaders collaborate to prepare work plans that can be executed with high degrees of reliability, thus improving the stability and predictability of work. As originally formulated by Ballard, the LPS works to achieve 'coordination by plan.' It differs from traditional planning in that it assumes that the uncertainty inherent in predicting when all constraints will be removed so that work can be executed can only be removed in the final instance by the team leader responsible for providing the labour needed for any given task. This is usually the trade crew manager or leader, who is termed the 'last planner'.

In an attempt to set the record straight in terms of defining what LSP is, Koskela *et al*. (2010) described its implementation as consisting of five steps:

1. Prepare a master schedule, reflecting the major project milestones.
2. Phase planning, which is commonly done using reverse-phase scheduling – i.e. tasks are scheduled in reverse order, from the desired delivery date working backwards, so that they can be performed at the 'last responsible moment', thus minimizing unnecessary accumulation of work in progress.
3. Prepare a lookahead plan for the medium-term future. For all the tasks in the lookahead plan, evaluate the state of their preconditions (usually using checklists based on the seven groups of task preconditions) (Koskela 2000). Work to remove the constraints, and move any tasks whose constraints have been removed into a list called the 'workable backlog.'

4. Prepare a weekly work plan in consultation with the last planners, and negotiate with all parties to achieve a plan that is considered feasible and to which all can commit. This is usually done in a ‘Last Planner’ meeting, which brings trade managers together to coordinate their activities over the following week. This meeting is different to standard weekly work planning meetings in that instead of management dictating a pre-conceived plan, selection of the tasks to be performed is done by the crew leaders on the strict basis of a ‘can be done’ filtering that ensures that only ‘mature’ tasks (from the workable backlog) are scheduled. The method avoids assignment of tasks that ‘should’ be done according to the lookahead or master plans, but which still have unresolved constraints.
5. Monitor execution and report the percent plan complete (PPC) in order to learn about planning failures and to institute continuous improvement.

Although later related to language action theory, LPS lacked an explicit theoretical basis in relation to coordination theory, which is founded on interdependencies between activities and resources. Nonetheless, the system provides a fruitful description of many of the factors involved. Phase planning, with its reverse scheduling technique, is based on close collaboration between different companies, and across trades. This is an example of mutual adjustment. Look-ahead scheduling also involves multiple trades in the preparation and implementation of the obstacle analysis, which can also be described as mutual adjustment, but at the level of preparation for production. However, there appears to be a weak relation between the classical LPS and coordination theory at the production level, where mutual adjustment is often required. The later addition of daily stand-up meetings into the system, as described by Macomber et al. (2005), addressed this shortcoming, but as pointed out in the analysis above this too has its limitations.

Our observations suggest that this need for coordination by mutual adjustment is often either solved on an ad-hoc basis as best can be managed by the different trades, for example by arranging joint building site inspections or through practical cooperation on a daily basis, or is not solved and leads to large buffers of work, with associated detrimental results. Ad-hoc efforts often fail since the tasks are highly complex, involving many actors who are not necessarily present at the construction site at all times – as illustrated by the example of multiple reciprocal interdependencies shown in Figure 1.

CONCLUSIONS

Traditional project planning only takes into account sequential interdependencies between tasks, even when there is evidence of additional reciprocal interdependencies. Experienced tradespeople and project managers solve the resulting challenges as best they can, through ad-hoc arrangements for closer collaboration and joint on-site inspections across trade and company boundaries or, as in the Israeli case, by building large buffers of work. A better theoretical understanding of different forms of interdependencies can be expected to help make it easier to manage and coordinate work processes whose dependencies are of a reciprocal nature. In particular, explicit recognition of the need for coordination by mutual adjustment can help guide the design of production control systems. Even for subprojects in construction that are dominated by sequential interdependence, reciprocal interdependence is likely to be found in the relationship with resources that are called for at other projects the subcontractors are involved in.

Our observations suggest that coordination theory based on explicit understanding of dependencies could contribute to the formulation and implementation of the Last Planner System. The system provides many correct descriptions in relation to mutual adjustment across trades in phase, look-ahead planning and weekly work planning; however, it is less developed in relation to the execution of the weekly production plan. Once the weekly work cycle has begun, teams are expected to complete the assignments to which they have committed themselves. As originally conceived, the LPS does not have any specific method for 'coordination by mutual adjustment' at this stage. Daily stand-up meetings improve the robustness of the system, but explicit identification of reciprocal dependencies according to coordination theory can be a crucial factor in their success.

For some tasks, work plans that are updated on a weekly basis are inadequate tools for coping with the existing interdependencies. We recommend that the prescription be made that specific subprojects be coordinated more closely through mutual adjustment by integrated tasks groups based on thorough analysis of dependency structures.

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