IF CPM IS SO BAD, WHY HAVE WE BEEN USING IT SO LONG?

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ABSTRACT

Why has the Critical Path Method (CPM) been used so widely for so long given its inability to produce predictable outcomes? For shedding light on this paradox, the formative period of the CPM is analysed from two main angles. First, how was the CPM embedded into the construction management practice? Second, what was the methodological underpinning of the development of the CPM? These questions are researched through a literature review.

In terms of embeddedness into practice, it turns out that the CPM morphed from being a way of production control, into a method for contract control. In consequence, the promotion of the CPM by owners has been crucial for pushing this method to be the mainstream approach to scheduling and production control.

Regarding methodological underpinning, it turns out that the CPM was developed as a way of optimization, as part of the quantitative methods movement. This movement was largely based on the axiomatic approach to research. In good alignment with that approach, there was no attempt to empirically test quantitative models and their outcomes. In this context, the unrealistic assumptions and conceptualizations in CPM did not surface in forty years.

These results are argued to be helpful in critical discussions on the role and merits of CPM and on the methodologies to be used in construction management research.

KEYWORDS

Critical path method, CPM, production planning, control, construction management

INTRODUCTION

The Critical Path Method (CPM) has been hailed as the most important innovation in construction management in the 20th century. Although having been widely criticized as inadequate to the task of controlling work in projects, it is still widely used and taught. Why has the CPM been so popular for so long given its inability to produce predictable outcomes? For shedding light on this paradox, the formative period of the CPM is first described and then analyzed from two main angles. First, how was the CPM embedded into the construction management practice? Second, what was the

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methodological underpinning of the development of the CPM? These questions are researched through a literature review.

EMERGENCE, DIFFUSION AND RECEPTION OF THE CRITICAL PATH METHOD

EMERGENCE

The CPM was developed by Morgan R. Walker from DuPont and James E. Kelley from Remington Rand in the late 1950's. DuPont recognized inefficiencies of traditional planning and scheduling methods, which was a catalyst for developing a new one (Lenfle & Loch 2010). Around the same time other similar applications to the CPM were developed. The Operational Research Section of the Central Electricity Generating Board in UK was also working on a similar idea. This group had an idea called "longest irreducible sequence of events", which they applied on a Keadby Power Station in 1957 for managing the shutdown and maintenance process (Hyatt & Weaver 2006). The precedence methodology was developed by Dr. John Fondahl when the U.S. Navy's Bureau of Yard and Docks contracted with Stanford in the late 1950s to report on "The Application of Operations Research and Other Cost Reduction Techniques to Construction" (Fondahl 1962).

Kelley and Walker start their article with the statement (Kelley Jr & Walker 1959): "Among the major problems facing technical management today are those involving the coordination of many diverse activities toward a common goal." They explain that large construction projects involve vast number of stakeholders with different skillsets and knowledge focusing on their particular problems, i.e. coordination of these interrelating activities is the very work of management. For addressing these issues, CPM was devised to manage variety of coordination and resource intensive projects by forming a topological network of discrete activities representing the overall project scope. CPM was intended to help to plan project resources, duration and optimize the cost in a systematic way. Kelley and Walker (1989) claim that the applications of CPM method are limitless.

HOW THE CPM DIFFUSED AND BECAME EMBEDDED IN CONSTRUCTION MANAGEMENT PRACTICE

The CPM method was enthusiastically embraced by the construction industry as a production management method. However, from the very beginning, the CPM started to be used in additional functions, especially in contract control by clients (Moder & Phillips 1964, Howell & al. 2011). Jaafari (1984) also reports other functions than planning to have been attributed to the CPM method. Interestingly, Laufer and Tucker (1987) found that the role of planning had degenerated 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). According to them, management focus had shifted, "overshadowing" in their words, more to control at the expense of planning. Further, the role of planning was often seen primarily as a scheduling and decision making, rather than planning of work and studying the work method alternatives. Thus, often the focus was on finding subjects responsible for deviations but not on improving the plan for the coming week. (Laufer & Tucker 1987)

The role of CPM in traditionally managed projects seems rather similar to earlier descriptions. The projects are managed from top down by establishing a schedule and enforcing the contracts (Howell et al. 2011). Within this context, the CPM method is used as a contract document for establishing work orders and construction schedules, controlling performance, assessing delays and change orders and managing progress payments (Jaafari 1984). Authority and communication protocols are clearly established to maintain the authority of the general contractor. Through the contracts, the general contractor has the authority to direct when and where the specialty contractors must work. Basically activities are treated as "black boxes", where means and methods for doing the work are left to the specialty contractor. Likewise, quality and safety are managed by inspection and enforcement (Sears 2010).

CRITICAL VOICES

Already in 1974, Peer claimed that the schedule resulting from CPM is of very limited use for site management, and the plans are quickly put aside before the work is really underway (Peer 1974). In turn, Applebaum (1982) contended that the bureaucratic management techniques (based on CPM, for its part) have an ineffective impact on the construction work, resulting in inefficiencies and irrationalities. In fact, the introduction of CPM seems to have created an additional but largely unnecessary layer of management:

> ...we have virtually two separate organizations; one for the management function and one for getting the work done. The two organizations do not coordinate their work, and they are characterized by different goals and viewpoints.

Indeed, in 1984, Jaafari reported six different criticisms addressed at the CPM (Jaafari 1984). It is illuminating to discuss some of the continuing topics of critique.

The CPM method focuses on the technological dependencies only, meaning that it does not support achieving the stable continues workflow and handovers between project stakeholders on the operational level (Peer 1974). This is however must be the backbone of the operational planning as that is the way sub-contractors optimize their resources. Continuity principle is the main objective of line of balance method (Seppänen 2009).

Goldratt argues that the main problem with traditional project management method particularly CPM is its misuse of safety times or buffers in activities. Buffers are added to each individual activity for accommodating the potential uncertainty, causing the effect that preparations for the next stage are not made because it is not clear when the previous activity will finish. As a result, activities are not ready to start when the previous activity actually does finish. Another argument is that the completed activities may not be released early, because of the expectation that, in the future, pressure will be applied to finish them early. The approach of the Theory of Constraints is to relocate the safety times in strategic positions; i.e. adding project buffers and focusing on finishing activities on time without "chunking" activities (Goldratt 1997).

Furthermore, it has been argued that the CPM can be used to identify major critical disturbances. All projects always face a residual uncertainty and randomness that will cause productivity variances, waste of capacity, schedule deviations and workflow instability. When reported properly, line of balance will immediately elicit deviations from planned productivity as opposed to the CPM, where identification of deviations often occurs too late (Seppänen & Aalto 2005). In the CPM, deviations are not clearly visualized as with the line of balance method.

Sacks and Harel (2006) state that traditional practices have led to zero-sum situation, adversarial relations, where different related parties isolated from the overall process tend to frame their decisions (Kahneman 2011). Framing means that contractors make their decisions from their personal perspective, which often is not aligned with the project goals as a whole.

DISCUSSION

The key observations made provide evidence on fundamental shortcomings of the CPM. Remarkably, until now all the critical insights on the shortcomings of the CPM have not been able to shake the dominant position of this method in construction. Some insights have led to development and promotion of new methods, such as critical chain and line of balance; however, these have not become mainstream methods. One possible contributing reason for the small impact of the critique may be that critical insights have not been emerged from evaluations of validity of CPM, but rather they have been introduced as isolated arguments. Indeed, it is difficult to find any systematic evaluation of CPM in construction, although there are examples of evaluations of project management tools in related fields (Alexander 1977). Thus, as a whole, the dominance of the CPM has continued surprisingly long in view of the problems pinpointed.

WHAT WAS THE METHODOLOGICAL UNDERPINNING OF THE DEVELOPMENT OF CPM?

THE LANDSCAPE OF IDEAS

In the first part of the 20^{th} century, the intellectual landscape of production management (and of management in general) was dominated by Scientific Management. This was a vibrant movement propelled by engineers that focused on production (Koskela & Ballard 2012). However, by the Second World War, Scientific Management had run out of steam, and a new scheme for management research was created in 1959. Two influential studies (Howell & Gordon 1959, Pierson 1959) suggested business research to be directed toward behavioural sciences, economics, and quantitative modelling. Management was separated from production, which was relegated just to an application area of managerial concepts and methods. (Koskela & Ballard 2012)

In philosophy of science, there have been two major approaches to acquire knowledge: inductive and deductive approach. In the inductive approach, one starts from observations on the world and tries to create, induce, theories that explain and predict it. In the deductive (or hypothetico-deductive) approach, one starts from ideas (hypotheses) and deduces specific claims on the world, the veracity of which will be then checked. One important strand of this approach is called axiomatic; in this case the hypothesis is presented mathematically as axioms.

At the time of the emergence of the above-mentioned new conception of management as a discipline, the hypothetico-deductive approach, especially in its axiomatic form, was dominating. It radiated from physics, to economics and quantitative modelling. In turn, inductive approaches were preferred in behavioural sciences.

AXIOMATIC APPROACH TO RESEARCH

The basic idea in the axiomatic approach is that we deduce consequences from a hypothesis. A representative account of the axiomatic method in physics is given by Hilbert, Nordheim and von Neumann (1926, referred to by Redei 2005), investigators of quantum theory. A targeted physical theory consists of three parts:

- physical axioms
- analytic machinery
- physical interpretation

In their scheme, the physical axioms are semi-formal requirements formulated for certain physical quantities and relations among them, and based on experience and observations. The analytic machinery is a mathematical formalism that contains quantities having the same relation among themselves as the relation between the physical quantities. The analytic machinery should be determined by the physical axioms, at least if they are strong and rich enough. Then, the physical interpretation provides the connections between the analytic machinery and the physical axioms.

However, Hilbert, Nordheim and von Neumann (1926) readily admit that this ideal description of axiomatization is not followed in practice. Rather (italics by present authors):

> In physics the axiomatic procedure alluded to above is not followed closely, however; here and as a rule the way to set up a new theory is the following.
> One typically conjectures the analytic machinery before one has set up a complete system of axioms, and then one gets to setting up the basic physical relations only through the interpretation of the formalism. It is difficult to understand such a theory if these two things, the formalism and its physical interpretation, are not kept sharply apart. This separation should be performed here as clearly as possible although, corresponding to the current status of the theory, we do not want yet to establish a complete axiomatization. What however is uniquely determined, is the analytic machinery which – as a mathematical entity – cannot be altered. *What can be* modified *– and is likely to be modified in the future – is the physical interpretation, which contains a certain freedom and arbitrariness*.

What is somewhat troubling here is that mathematical formalism is given the lead role, one develops that first, and then seeks for a physical interpretation. Another interesting observation is that these authors do not rush to mention empirical testing of a physical theory so developed. However, this seem compatible with the vague role given to physical interpretation: how can we reliably subject a theory to an empirical test if the physical interpretation is still containing “a certain freedom and arbitrariness”.

The physicist Dirac, a Nobel laureate in 1933, gives another interesting testimony.

He may be seen to take an extreme position regarding the relative importance of mathematical beauty and empirical testing (Dirac 1963):

> I think there is a moral to this story, namely that it is more important to have beauty in one's equations than to have them fit experiment.

Dirac (1963) takes a more moderate position when expanding the topic:

> It seems that if one is working from the point of view of getting beauty in one's equations, and if one has really a sound insight, one is on a sure line of progress. If there is not complete agreement between the results of one's work and experiment, one should not allow oneself to be too discouraged, because the discrepancy may well be due to minor features that are not properly taken into account and that will get cleared up with further developments of the theory.

On the other hand, Dirac (1963) does not reject experimental testing – one can be "quite happy" if there is a fit between theoretical results and experiment:

> If the physicist knows how to calculate results and compare them with experiment, he is quite happy if the results agree with his experiments, and that is all he needs.

Thus it can be concluded that the style of axiomatic physical research prevalent in the 1950's was slightly distorted in comparison to the long historical tradition of the hypothetico-deductive approach in general: the comparison of the prediction to the empirical reality was not emphasized, even if not rejected.

AXIOMATIC METHOD IN PRODUCTION MANAGEMENT

At the emergence of modern production management (into which the Critical Path Method falls) in early 1960's, quantitative methods were the dominant methodological choice. To which extent did they inherit methodological ideas from contemporary physics?

Indeed, the primacy of mathematical formalisms was (and still is) a methodological guideline for this type of research, as characterized by Bertrand and Fransoo (2002):

> In fact the researchers look at the operational process or the operational decision problem through the looking glass of the mathematical models that can be analyzed.

This approach led to looking at idealized problems, amenable for mathematical representation. Bertrand and Fransoo (2002) comment (OM refers to operations management):

> …idealized OM problems were not intended as scientific models of real-life managerial problems, in the sense that the models could be used to explain or predict the behavior or performance of real-life operational processes. They were just partial models of problems that operations managers may encounter. The

> models were partial because all aspects of the problem that were not related to the method or technique used were left out, the implicit assumption being that these aspects would not affect the effectiveness of the problem solutions based on these models. *It was left to the practitioner to include these aspects into the solution based on his knowledge of reality* and of the partial model of the problem.

Thus, the central argument for focusing on idealized problems is based on the assumption that practitioners can "fill in" what has been left out from the problem definition. But can they? We return to this question below.

Similarly to the discussed trends in physics, there seems to have been little effort in operations management to validate the axiomatic models created (Bertrand & Fransoo 2002). Indeed, in their overview on methodologies in operations management, Bertrand and Fransoo (2002) usefully characterize the missing type of research for validating quantitative models:

> Quantitative model-based empirical research is concerned with either testing the (construct) validity of the scientific models used in quantitative theoretical research, or with testing the usability and performance of the problem solutions obtained from quantitative theoretical research, in real-life operational processes. […] these core processes are identified as implementation and validation. Quantitative empirical research is still in its infancy and there therefore exists much less consensus about what is good quantitative empirical research than about what is good quantitative axiomatic research.

Bertrand and Fransoo (2002) end up recommending validation and testing for the future of operations research (OR), that is the field of quantitative methods in operations management (italics by current authors):

> The discussion above shows how OR research can become more effective. OR should study models that are closer to real-life operational processes. In fact, *models should be studied which can be validated as real-life processes, and also the results of the analysis should be tested in real life.* In such a way, feedback is obtained regarding the quality of the model used for and the quality of the solutions obtained from the analysis. Thus theoretical quantitative research should be combined with empirical quantitative research.

Thus, in hindsight, the field of quantitative methods in production/operations management followed surprisingly closely the methodological paradigm of physics, and measures to rectify related shortcomings have been suggested only recently. In passing, it is interesting to note the long-standing relevance problem of operations management – unfortunately a discussion on the connection between the initial focus on starkly idealized problems and the missing validation of models, on one hand, and the lack of relevance of those models, on the other hand, would deviate from the main topic of this paper.

CRITICAL PATH METHOD AS AN INSTANCE OF AXIOMATIC MODELLING

The Critical Path Method falls into normative quantitative methods: it is an optimization model, where the duration of the project is minimized. Oddly, this feature seems to have been diluted on both sides, in the field of quantitative methods and in construction management, although CPM may be the most popular optimization model ever created. Cogently, Bertrand and Fransoo (2002) do not mention CPM at all in their overview article on quantitative modelling in operations management, and in construction management, CPM is nowadays offered as a planning and management method rather than as an optimization model.

The foundational hypothesis in CPM is that a project consists of deterministic tasks, which have mutual dependencies, and that by finding the shortest possible order of the tasks the best possible, that is, optimal, plan can be identified. However, this implies that also the tasks, as they have been designed/planned, must be optimal. Namely, if we would try to create an optimal plan from a collection of tasks where even just one is non-optimal, we would fail – the result would not be optimal: by switching to the optimal task formulation regarding that non-optimal task, we could provide a better overall plan. Thus, we cannot create an optimal plan from non-optimal tasks.

Unfortunately, it seems that exactly the mentioned methodological distortion, neglect of validation, has effectively played a role here for forty years: before Ballard (2000), nobody cared to verify whether in the actual application of the critical path method, the best possible plan gets realized. Ballard noticed that typically only around half of the tasks in a weekly plan, based on CPM, end up being realized as planned. This means that half of the tasks are non-optimal, assuming that tasks as planned are optimal. Unfortunately, this effectively undermines the rationale of the CPM: what is proposed to be an optimal plan cannot possibly be optimal in practice, as it is generally not possible to execute tasks in the optimal way[1].

A root cause analysis of the situation described reveals that abstracting away of other inputs to a task than the completion of the precedent task is one major cause for non-optimal execution of tasks (Koskela & Ballard 2006). Obviously, this is the very idealization required for rendering the problem of planning mathematically amenable.

Now, it is opportune to return to the question: Can practitioners fill in what has been left out in idealization? Jaafari (1984), after reviewing the six themes of critique against the CPM, seems to agree that they can and should:

> …there is nothing inherently wrong in either CPM concept or the subsequent schedules resulted from its analysis, the fault lies in the way it is applied in practice.

[1] A reviewer of the paper held that this inference is not valid, but rather the question should be framed as one of plan reliability. We disagree with this view, already as the concept of plan reliability wrongly implies that the outcome of the implementation of a plan depends on the qualities of the plan. Surely they influence, but so do the availability of resources, the managerial commitment, the ways of pushing tasks into execution, and many other corresponding contextual factors. In our view, allegedly optimal plans, when consistently leading to worse outcomes than prescribed in the plans, cannot be the best possible. - However, the concept of plan reliability may be useful when applied with the *ceteris paribus* condition (all other things remaining the same); then it can be used for comparing alternative plans.

This conclusion of Jaafari resonates with the views subscribed by promoters of quantitative methods in operations management, as discussed above. Nevertheless, we disagree on this point. Already the example of task inputs abstracted away from the conceptualization of the CPM, leading in practice to chronic problems in starting tasks, suggests that it is hardly possible for a practitioner to fill in for practical implementation what has been idealized in the model. More generally, the widely reported failure of the CPM to practically support site management provides evidence to the same effect.

Moreover, the role of idealization may be more critical than just something to be filled in by practitioners. Rather, the direction of influence may be just the opposite. As argued by Morris (1997), the application of quantitative/operations research models in military planning during and after the Second World War led to the development of "Modern Project Management" methods. It is no exaggeration to say that the discipline of project management evolved around the Critical Path Method, inheriting its assumptions and conceptualizations. Arguably, practice has not enriched idealization towards realism, but rather idealization has impoverished practice resulting in lost realism.

CONCLUSIONS

Regarding methodological underpinning, it turns out CPM was developed as a way of optimization, as part of the quantitative methods movement. This movement was largely based on the axiomatic approach to research. However, in good alignment with that approach, there was no attempt to empirically test quantitative models and their outcomes. In this situation, the unrealistic assumptions and conceptualizations in CPM did not surface in almost forty years.

In terms of embeddedness into practice, it turns out CPM morphed from being a way of production management, into a method for contract and task control. In consequence, the promotion of CPM by owners has been crucial for pushing this method to be the mainstream approach to scheduling and production control.

Thus, based on the analyses made, we can provide an initial answer to the question posed. The dominant use of CPM for construction planning and management for over fifty years has been supported

- by a methodological shortcoming: the method was never systematically tested for empirical validity, as well as

- by subtle shifts in the purpose of its use, especially from production management to contract management and to control more generally; as far as the purpose of CPM shifted to control, the need for validation of the optimality of the solution diminished – that CPM provides a baseline for control was more or less sufficient.

- In terms of methodology of construction management research, this outcome emphasizes the role of testing, validation and evaluation of solutions proposed. Of course this guideline is an organic part of the methodology of design science research, which unfortunately has been available only in the last ten years or so.

REFERENCES

Alexander, J. W. (1977). Management in Archeology: Scheduling Techniques Applied to Archeological Projects and Their Evaluation. A Thesis in Anthropology Submitted to the Graduate Faculty of Texas Tech University in Partial Fulfilment of the Requirements for the Degree of Master of Arts.

Applebaum, H. A. 1982. "Construction management: Traditional versus bureaucratic methods." Anthropological Quarterly**,** 224-234.

Ballard, H.G. (2000). The Last Planner System of Production Control. A thesis submitted to the Faculty of Engineering of The University of Birmingham for the degree of Doctor of Philosophy. School of Civil Engineering, Faculty of Engineering, The University of Birmingham.

Bertrand, J. W. M., & Fransoo, J. C. (2002). "Operations management research methodologies using quantitative modeling." International Journal of Operations & Production Management, 22(2), 241-264.

Dirac, P. A. M. (1963). "The evolution of the physicist's picture of nature." Scientific American, 208, 45-53.

Fondahl, J. W. (1962). "A non-computer approach to the critical path method for the construction industry."

Goldratt, E. M. (1997). Critical Chain, North River Press.

Hilbert, D., Nordheim, L., and von Neumann, J., (1926). "Über die Grundlagen der Quantenmechanik", in: Collected Works, Vol. 1 Logic, Theory of Sets and Quantum Mechanics, A. H. Taub, ed., 1962, Pergamon Press, pp. 104-133.

Howell, G., Ballard, G., and Tommelein, I. (2011). "Construction Engineering—Reinvigorating the Discipline." Journal of Construction Engineering and Management, 137(10), 740-744.

Howell, J. E., & Gordon, R. A. (1959). Higher Education for Business. Columbia University Press, New York.

Hyatt, C., and Weaver, P. (2006). "A Brief History of Scheduling." Melbourne, Australia: Mosaic Project Services Pty Ltd.

Jaafari, A. (1984). "Criticism of CPM for project planning analysis." Journal of Construction Engineering and Management, 110(2), 222-233.

Kahneman, D. (2011). Thinking, Fast and Slow, Farrar, Straus and Giroux.

Kelley, J., and Walker, M. R. (1989). "The origins of CPM: A personal history." pm network, 3(2), 7-22.

Kelley Jr, J. E., and Walker, M. R. (1959) "Critical-path planning and scheduling." Proc., Papers presented at the December 1-3, 1959, Eastern joint IRE-AIEE-ACM computer conference, ACM, 160-173.

Koskela, L., & Ballard, G. (2006). What is Lean Construction – 2006. Proc., Construction in the XXI Century: local and global challenges - ARTEC - Rome, Italy, October.

Koskela, L., Ballard, G. (2012). Is production outside management? Building Research & Information, Vol. 40, Iss. 6.

Laufer, A., and Tucker, R. L. (1987). "Is construction project planning really doing its job? A critical examination of focus, role and process." Construction Management and Economics, 5(3), 243-266.

Lenfle, S., and Loch, C. (2010). "Lost Roots: How Project Management Came to Emphasize Control over Flexibility and Novelty." California Management Review, 53(1).

Moder, J. J. & Phillips, C. R. 1964. Project Management with CPM and PERT. Van Nostrand Reinhold Company.

Morris, P. W. (1997). The management of projects, Thomas Telford.

Peer, S. (1974). "Network Analysis and Construction Planning." Journal of the Construction Division, 100(3), 203-210.

Pierson, F. C. (1959). The education of American businessmen: A study of university-college programs in business administration. McGraw-Hill.

Rédei, M. (2005). John von Neumann on Mathematical and Axiomatic Physics, in: The Role of Mathematics in Physical Sciences (pp. 43-54). Springer, Netherlands.

Sacks, R., and Harel, M. (2006). "An economic game theory model of subcontractor resource allocation behavior." Construction Management & Economics, 24(8), 869-881.

Sears, S. K., Sears, G. A., & Clough, R. H. (2010) "Construction project management: a practical guide to field construction management." John Wiley & Sons.

Seppänen, O. (2009). "Empirical Research on the Success of Production Control in Building Construction Projects." PhD, Helsinki University of Technology Espoo, Finland.

Seppänen, O., and Aalto, E. "A Case Study of Line-of-balance Based Schedule Planning and Control System." Proc., 13th Conference of the International Group for Lean Construction, University of New South Wales, 271-279.