CRITICAL EVENTS IN CONSTRUCTION PROCESS

Kirsten Jørgensen[1] and Grane M. G. Rasmussen[2]

Department of Planning and Management of the Built Environment, Technical University of Denmark, 2800 Lyngby, Denmark

Function failures, defects and poor communication are major problems in the construction industry. These failures and defects are caused by a row of critical events in the construction process. The purpose of this paper is to define "critical events" in the construction process and to investigate cause-effects of failures and defects in the construction industry by using an analytical approach (The bowtie model) which is developed in the accident research. Using this model clarifies the relationships within the chain of failures that causes critical events with undesirable consequences. In this way the causes of failures and the relationships between various failures are rendered visible. A large construction site was observed from start to finish as the empirical element in the research. The research focuses on all kinds of critical events identified throughout every phase during the building process and includes all participants in the construction project. A general result from the analysis was that critical events that occurred when the site was not using Lean Construction evolved much longer than critical events that occurred in the period when Lean Construction was used. Another result was the usefulness of the analytical model for visualising the cause-effect of failures and defects in construction.

Keywords: construction process, cause-effect analysis, failures, lean construction.

INTRODUCTION

It is always in the clear light of hindsight that one discovers what one should have done differently. The fact of the matter is that very often what one did was something one had done before (perhaps many times) and everything went well – so why not this time?

This paper examines the cause-effect relations for function failures and defects in the construction industry.

Failure is seen in connection with an undesirable consequence – but what actually failed, what kind of failure was it, and why is it so difficult to recognise the causes of failure in a way that helps us see the danger signals and take preventive action?

Failure in construction is generally related to defects and shortcomings in the finished building. Such defects and shortcomings are discovered either when the building is handed over – such as conditions that do not meet the owner's justified expectations on the basis of agreements and contracts – or a long time after the hand-over, such as problems of damp, cracks or, in the worst case, collapse.

Quite a lot of research focuses on construction materials and methods; the aim is to find the right methods and the right materials. But despite a lot of knowledge about

[1] kirj@man.dtu.dk
[2] gmgr@man.dtu.dk

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which materials are good and which methods work, a lot of defects and shortcomings still occur in building work (Danish Enterprise and Construction Authority 2009).

The construction process itself is also the subject of extensive research and development aimed at improving the process and minimising losses, including defects and shortcomings, both during the construction process and in the finished building. Methods such as ‘Construction Excellence’ and other quality assurance systems were constructed. Over the past decade, concepts such as ‘Partnering’ and ‘Lean Construction’ have been in focus (Koskela 1999, Dahlgaard-Park *et al.* 2007, Hellard 1993). Research into defects and shortcomings in finished buildings as well as during the construction process indicates that many of the causes lie in the project planning phase, in the co-ordination and communication during the building’s construction, and in the lack of quality in the construction contractors’ work (Henriksen *et al.* 2006, Douglas *et al.* 2008). Building and the construction process are described as a complex, stochastic process with many players. Every time it is a new product with new methods, new crew, new conditions, timeframe and finances, new suppliers, etc. that together make up the framework for the process that the construction runs through from idea to being taken into use (Kreiner 2005, Josephson *et al.* 2005, Douglas *et al.* 2008). In such a process, decisions will be made on an inadequate foundation and problems will arise that must be solved on the basis of the given situation and options. There will always be things that in one way or another can be called failures in relation to the given situation. But if such failures are discovered and corrected, i.e. solutions are found, it is more of an open question as to whether they are regarded as failures as such or ‘merely’ circumstances that reduce the efficiency of the construction process and cause quality and cost problems. This paper gives examples of how failures during the construction process can be revealed, and of the interdependence of such failures. For the purposes of this analysis, methods and conceptual understandings derived from accident research have been adapted to create a new way of mapping failures in the process of construction. The intention is to provide a clear analysis of failures, including what happens, why it happens, and the ways matters can be improved in the individual construction phases.

What is failure?

We should distinguish two definitions:

The way in which failure is understood by the formal system, which is set up to find out who is culpable in purely legal terms and who is liable in purely insurance terms. Failure in this connection is related to defects and shortcomings in the finished building and is a matter for the building owner and user. (Nielsen *et al.* 2004)

The defects and their consequences that occur during the construction process from idea to handing over. The consequences of such defects can end up among the formal defects and shortcomings, but they can also be, and often are, resolved during construction, but with consequences for the project’s budget, timetable and the construction crew, and with a waste of raw materials, etc. (Jørgensen 2008)

A thorough examination of the literature about how the term ‘failure’ is understood and used shows that there is a very great variety of points of view. The term is often defined or explained using other terms, such as ‘faults, mistakes, shortcomings, losses’ etc.

Examples of how construction researchers describe or define the meaning of these terms include ‘sudden situations or situations where new and unpleasant effects arise’

(Kreiner 2005), ‘that project materials, building materials, constructions or parts of buildings lack properties that have been agreed or are required by law’ (Nielsen *et al.* 2004), ‘circumstances that prevent the builders carrying out their work efficiently’ (Apelgren *et al.* 2005). Accident research also defines faults as the causal explanation of accidents. In this branch of research, ‘faults’ are specified in various categories, such as ‘faulty acts, functional faults, and faulty sources’ (Reason 1990); ‘omission, incorrect execution, irrelevant action, incorrect sequence, incorrect time’ (Swain 1974); ‘experience-based errors, rule-based errors, knowledge-based errors or deliberate errors’ (Rasmussen 1997). Common to both construction research and accident research is that we speak of ‘causes’ for what precedes an event and ‘consequences’ for what follows the event. This means that there is a big overlap in the way the terms ‘failure’ and ‘accident’ are understood.

METHOD

Recognising the lack of clarity and conceptual confusion in the use of the term ‘failure’ in construction, let us look at the understanding of the term ‘accident’, which is a relatively well-established concept. To start with, let us look at Rasmussen’s model of the anatomy of accidents (Rasmussen 1997), in which the critical event is the point when it becomes clear that something has gone wrong. We can transfer this idea directly to the term ‘failure’, as illustrated in Figure 1, where the critical event is where a failure becomes visible and perhaps discovered.

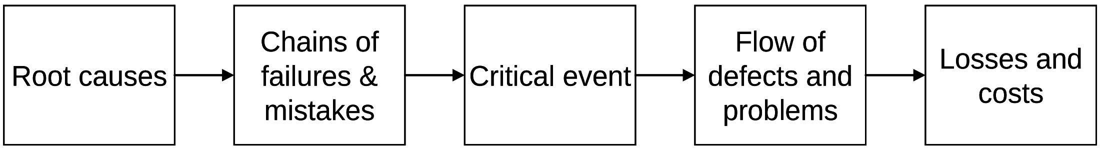

Figure 1: Illustration of the model for the anatomy of failure

A definition of the term ‘failure’ based on such a sequential model makes it possible to put the various other terms used into relationship with each other. The aim is to create a common language in which the terms can be used in a clearer way. This means that terms such as ‘faulty acts’, ‘functional faults’, ‘interruptions’, ‘delays’, ‘lack of precision’, etc. become causal explanations for the critical event, while ‘defects’, ‘damage’ and ‘losses’ become consequences.

On the basis of this sequential model, we can look at the term ‘failure’ as something that covers causes, the critical event and consequences. In other words, ‘failure’ is defined as a series of relationships characterised by:

Being due to a number of defects and pre-conditions whose combination generates an undesired situation/critical event, and

Resulting in a number of consequences for the rest of the construction, which often create delays, increase costs, and require resources, and can also be factors in the occurrence of new failures later in the construction process.

This means that failure does indeed include faults, mistakes, shortcomings, damage, etc., but in a certain sequence.

At the same time, it must be admitted that the term can be difficult to grasp unless you relate it to something definite, such as where the failure occurred or for whom it occurred. But making the term ‘failure’ relative it becomes possible both to make the term precise and to open it up to include all forms of inappropriate activity in the construction process. Precision can be gained by adding an adjective for the type of failure, e.g. design failure, process failure, communication failure, execution failure, materials failure, finishing failure, and so on. With this understanding, it will often be the case that one type of failure will be among the causes of another type of failure. In other words, in this sense failure can be something that goes wrong, something that is a cause, or something that is a consequence, entirely depending on your perspective. However, the advantage of this is that one can define the individual failure with precision, which means it also can be analysed with precision. At the same time, the number of failure analyses and the loosely coupled inter-relationships between them mean it is possible to 'flow' between them when analysing a failure process. The result is that it is possible to map what is generally described in construction as chaos and confused relationships, coincidences, etc. This will be illustrated later with a concrete example.

The Bow Tie – an analytical method from accident research

In accident research, especially in the high-risk area, fault tree analysis and event analysis are among the methods used to analyse the causes and consequences of accidents. One analytical method that combines these analysis forms is called the 'bowtie' because of its shape (Worm 2008). If this analytical method is used to model the term 'failure', a bow-tie analysis of failure will look like this:

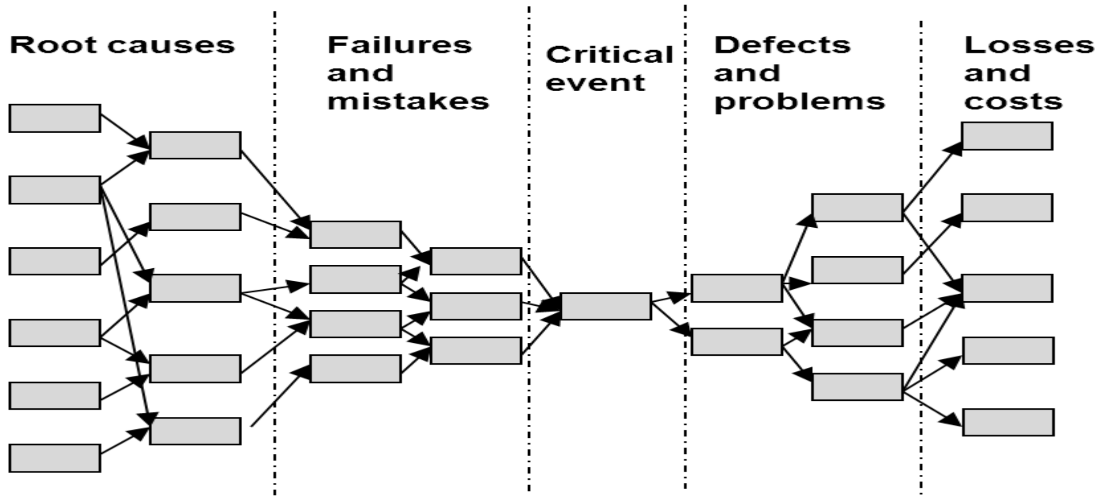

Figure 2: Illustration of the bow-tie analysis of failure (ceasing to function)

Once the central or critical event has been observed, one can use the sequence of consequences to describe the right-hand side of the model. The elements that make up the right-hand side are all the circumstances with the potential to exacerbate the consequences and their after-effects. In principle, the consequence side represents the effects that should be prevented or minimised. Similarly, the left-hand side represents circumstances that together generate the foundation for the occurrence of the critical event. Here too, there are many different circumstances and mistakes that, because of their synchrony, taken together explain the critical event. The model can also be used to illustrate where barriers can be raised either to prevent the critical event occurring or to minimise its potential consequences. The theory is that once an accident is analysed, the barriers that could affect the flow on both the left and the right-hand side of the critical event can be identified. For example, if one or more of the chains on the left-hand side can be prevented, the other circumstances will not result in a critical event. Similarly, a barrier on the right-hand side can limit the spread of consequences or minimise their gravity – e.g. if there is a fire, a sprinkler system would make it possible to extinguish it early or reduce its spread. So this model makes it possible to analyse loosely coupled causal relationships and consequences for specific critical events, and can therefore both describe and illustrate any kind of failure.

Case project

To verify the analytical method described above, a building project was monitored throughout the construction process; critical events were observed and both the circumstances preceding them and the resulting consequences were described.

The building project was a large housing project in which the principles of Lean Construction were followed and in which both the processes and collaboration partners were well under control. The final result was a very good construction job. Nevertheless, there were failures during construction and they affected the resources, time spent, and quality (Jørgensen 2008). A total of 55 important critical events during the construction process were analysed. Each critical event was analysed separately with both a left and a right-hand side. Moreover, the use of the "bow tie" made it possible to link the individual critical events with each other and get an overview of all the processes and their mutual relationships. The red, blue and green used in Figures 3 to 7 are aimed at showing how almost all these critical events had an effect in terms of time, costs, and the use of resources of both materials and manpower.

To illustrate the use of the analytical method, an example is given in Figure 3 of one individual bow-tie analyses of failures identified, and in Figure 4 how the various critical events – and therefore failures – are inter-related. This figure also gives an overview of all 55 critical events.

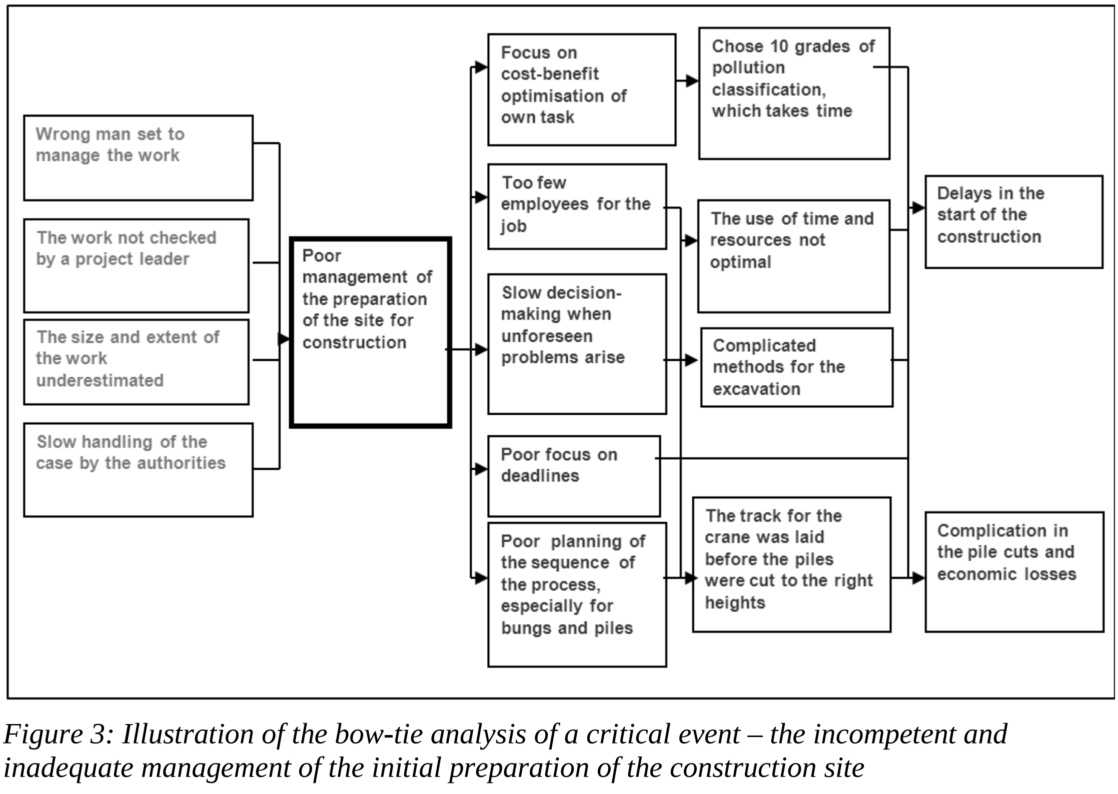

Figure 3: Illustration of the bow-tie analysis of a critical event – the incompetent and inadequate management of the initial preparation of the construction site

The left-hand side in Figure 3 shows the background for the poor management and the right-hand side shows its overall consequences.

This series of bow-tie analyses show how there can be a flow of inter-relationships between critical events in a process stage, leading to new critical events at later stages. On the other hand, they also illustrate how the relationships are not unambiguous and that at each stage there are other factors that so to speak support and aid the development of the individual critical events.

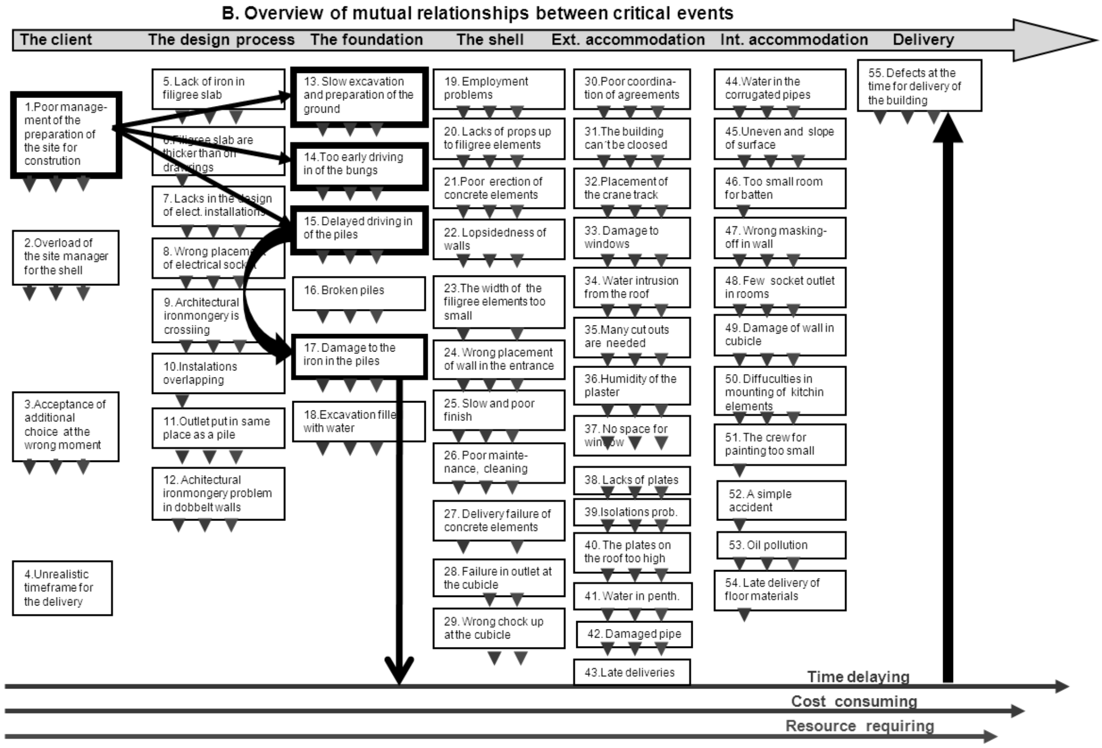

Figure 4: An overview of the 55 critical events in the construction project. The inter-relationships between the bow ties used in the examples are marked

This kind of analysis, focusing on critical events in individual phases of the building project, makes it possible both to focus on critical events in the individual phases and at the same time put each critical event in relationship to others where such a relationship exists. In this way, it was also possible to show a connection between an inappropriate composition of the project management for the building shell and the quality of the construction of the shell, which later had consequences all the way through the rest of the construction process. It was also possible to clarify the link between deficient electrical planning and a number of critical events later in the construction phase during the internal fitting out.

RESULTS

The fundamental results of the analysis of the 55 failures are:

Failures that occur at the start of construction in particular have a domino effect throughout the whole process, in part because all subsequent processes must adapt to the shortcomings in the start phase, but also because in general any failure will affect the project’s schedule and cost. Among other things, this means that if too much time is spent on the start phase of the construction process, those who lose out are those who have to finish the building. Failures often arise because decisions are taken at one stage of the process without being followed up and integrated in subsequent stages, where ‘business as usual’ is the ruling maxim. Some of the failures thus arose because further action was not planned when decisions required it.

The fact that meetings of foremen, the Last Planner System, and a good construction crew can redress problems of failure and ensure delivery of a good building, does not mean there are no consequences in terms of time and cost.

The construction took the form of a development project with 70% own project planners and craftsmen. Construction was based on Lean Construction principles, but this organisational form was not applied to foundation work and building the shell. This partly explains the failures that occurred in these first stages of the construction process. So some things went well and some things went wrong.

What went wrong?

A common feature of the failures registered is that they occurred during work that would not normally be expected to involve any special risk and was not therefore subject to any close scrutiny. For this kind of work, the working methods are regarded as known and it is normal practice to co-ordinate detailed planning on site. The failure analysis here showed that quality ends up depending on the individual craftsman's sense of quality. The expertise and meticulousness of the individual craftsman are decisive factors in the number of failures and how they are tackled to avoid fatal consequences. In the final analysis, expertise and meticulousness are what create good buildings and minimise failures. More thorough and co-ordinated project planning of the building process could have ensured less dependence on the expertise and sense of quality of the individual craftsmen. The results show that constant sub-optimisations in individual professional fields often create problems for the work that comes after.

Another typical cause of critical events is found in deliveries. When suppliers deliver faulty products, the supplier himself must rectify the problem. Defects and their rectification, however, have consequences for both time and quality in the building process, causing failures to arise in other circumstances later in the process.

Visualising critical events through the bow-tie model shows that time delays have a domino effect throughout the rest of the construction. This results in changes in schedules and the sequence in which work is done. In the final phase of construction, the consequences turn up in the form of lack of time to redress defects and work that is unfinished before the building is handed over.

Most of the defects and shortcomings registered during the shortcomings inspection are the visible shortcomings. So it is mainly finishing problems that need putting right. The shortcomings are primarily related to the work of painters, carpenters and kitchen fitters – i.e. the last jobs in the construction process. The retrospective analysis of critical events using the bow-tie model makes it possible to identify small failures with large consequences. When you confront the people responsible for the first link in the chain of failures, the usual response is, "That's what it's like in construction; it can't be avoided."

What went well?

In the project planning phase, great weight was placed on risk aspects, and those responsible for the project aimed at good practice and safe methods when planning and during the construction itself. Both the head of the project and the construction process manager succeeded in keeping to the principles of Lean Construction with regard to planning, meetings, involvement, etc. Communication and knowledge-sharing between the parties in the construction functioned in a way that ensured that work was understood and carried out as planned. This meant that many failures were discovered early so that they did not have the chance to develop into critical events with serious consequences for the construction.

In the case project, predetermined quality procedures and a comprehensive information system that both the project planners and the construction crews could draw on were used as a basis for the work. Among other things, the information system contained quality control forms for a very large number of tasks and experience from earlier jobs. We want particularly to highlight the foremen's meetings, which were the most important factor in both collaboration and the whole construction process. These meetings discussed the co-ordination of future work, site logistics, planning for equipment such as lifts, tackle, cranes, etc.

DISCUSSION

In this case study three characteristics came to light when the type and scope of shortcomings were considered. The first characteristic was the way the various parties differed in their sense of finish. There would have been a considerable reduction in the number of points on the owner's list of shortcomings if a provisional review of shortcomings and ways to redress them had been made before the building was handed over. The second characteristic was the domino effect that time overruns in any part of the work has on the final construction time. This phenomenon could be compensated for by introducing into the schedule time for the provisional rectification of shortcomings, so it would be possible to reach the target. This was included originally in the overall schedule for the case project, but this time was used up by diverse delays, which meant that at the end of the construction process the critical finishing work was squeezed in time.

The third characteristic was the lack of clear responsibility – that is, the individual professions should be held responsible to a greater degree for delivering the promised quality before the building is handed over. There should be consequences for failing to do so. On the basis of the results, the assessment is that many of the causes of failure could have been avoided by using skilled craftsmen who are involved in the planning of the processes. This could have ensured a greater degree of responsibility for the process. Much indicates that either a joint venture agreement or belonging to the same organisation with the same top management is vital for this feeling of co-responsibility among those carrying out the work. Having a good crew who know each other from earlier projects and where the foremen in particular have worked together before makes cross-disciplinary planning easier. It also helps create a sense of responsibility towards each other, so that later work can be carried out as it should. In the case project, there is much to indicate that the objective agreed at the first kick-off meeting was successfully achieved. The kick-off meeting was also highlighted as something positive that contributed to good collaboration – things are easier when you know each other. The results of this study have shown that there is a need for the project planning to think through the construction process and identify steps where any foreman or construction manager could have difficulty in getting the job done. Consultants and architects should not assume that those carrying out the work or the site management know or have the expertise to work out the optimum work procedure. Particular focus should be on what might be misunderstood or overlooked. The planning of ordinary aspects of the work must be viewed with as much seriousness as complex aspects, not least because they make up the largest part of the project and because any uncertainty about the completion of a job depends heavily on the crew doing the work. Similarly it is essential to make clear any special factors that must be taken into consideration during construction, so that both the craftsmen and the project management are in no doubt about what the objectives were during project planning.

The results of this case suggested that the advisers did not have the same understanding of the importance that time overruns and reductions in quality would have for the finished building. So it would be worth considering whether it should be mandatory for the contractor and the consultant to make a review of the project planning material before construction starts.

CONCLUSIONS

The implementation in recent years of new methods such as Partnering, Lean Construction, etc. are examples of a more targeted way of making the construction process more effective, but experience shows very great variation with regard to the success rate of these ideas. The recommendation therefore is that we need to start developing our knowledge with a focus on the underlying factors in the causes of defects and shortcomings.

Using the bow-tie model from accident research as an analytical tool helped make relationships visible and gave us an overview. This analytical method focuses on the underlying causes of failures that later become the causes of critical events, instead of on the shortcomings that are first registered during the owner's shortcomings review when the building is handed over. This is what enabled the bow-tie model to prove itself a good tool for both creating an overall picture and bringing the details to light. This retrospective analytical method gives a combination of results that makes it possible to determine the typical barriers and prepare targeted initiatives to avoid and redress similar critical events in future construction work. Just as is the case with safety and risk, the causes of critical events must be sought in management concepts, organisation, production, expertise, culture, technology, etc. As in this area, the causal relationships are multi-functional and loosely coupled.

The study has shown that a lot of failures can be avoided if there is good collaboration between the players throughout the building process. If the communication between the parties functions well and if everyone is involved and there is mutual respect and understanding for each other's work, this has a great impact on time consumption and quality. A lot of failures can be prevented or minimised when there is understanding about the work that comes next.

In situations where the conditions for the process cannot be optimal, it is necessary that responsibility is taken for decisions and any resulting consequences are properly managed. If choices of any kind are made that might have consequences for the rest of the construction in terms of schedule, quality or cost, these choices must be allowed for in the overall plans. Decisions must not be taken at the expense of the overall construction time, quality or cost. The conclusion is that no process can be seen in isolation, but must be seen in the larger context of which it is a part. No process should be started unless there has been an assessment of its consequences for the processes that come afterwards.

In this case project, the co-ordination of the construction work has without any doubt contributed to minimising misunderstandings during the work. Among other things, the co-ordination has included project and process reviews by consultants and contractor before the work started. Much of this is what is promoted as good practice in a construction project, including in descriptions of how Lean Construction should be implemented. But the problem is that the construction industry is a difficult industry to make changes in. Documenting failures in the building process, as in the examples given in this paper, makes visible how the individual players, especially in the first stages of the process, have quite a significant impact on the final result. This has probably been said on many occasions, but not documented as clearly. Perhaps this evidence can contribute to more people taking the planning stage preceding construction more seriously.

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