Causal structure framework of man-made disaster in construction

A Suraji
University of Andalas

Corresponding author: akhmad.suraji@eng.unand.ac.id

Abstract: Construction accident is a man-made disaster. Causal factors of a construction accident could lie dormant at the project conception, design, and construction stage. Investigating the causal factors is, therefore, inadequate if directed only to operative errors, and the contractor’s management or organisation failures. A systematic investigation should also cover management or organisational failures initiated by the designer, the client’s team, and the client. This would lead to the need for a practical method of the accident investigation by which the operational errors, and management or organisational failures can be revealed comprehensively. This paper presents a constraint-response analysis of causation of construction accidents (CRACCA). It is a model illustrating a generic network of factors in construction accident causation. CRACCA proposes that construction accident causation consist of (1) accident events, (2) proximal factors, and (3) distal factors. The accident events represent accident occurrences and their consequences; the proximal factors represent deficiencies of the construction process; whilst the distal factors represent precursors generating the proximal factors. Both the proximal and distal factors are considered as factors stimulating the increased risk of construction accident. The distal factors are characterised as constraints applied to, and responses by, participants in the construction project. These constraints and responses constitute management actions taken by clients, the client’s team, the designers or the builders. In this way, the model will assist investigators to structure more readily the causal factors, and determine potential or predominant factors leading to construction accidents. In this paper, the constraint-response theory is briefly described. The generic structure of the causal network is presented. The default features of the model are introduced. The paper also illustrates procedures using CRACCA.

1. Introduction

1.1. Nature of accident investigation
Investigations of accident causation aim to identify causes of accident events and reconstruct the causal processes. The current theories of accident causation [1], [2], [3], [4], [5] suggest the causes of the accident events could lie dormant upstream of the boundary of front line production. This implies that the investigations should be directed not only to reveal the events and failures of technical conditions or operational situations leading to the accident events, but also management or organisational factors that create these conditions or situations, known as latent failures [1]. The investigations should also consider environmental factors that stimulate the latent failures so that the root causes of the accidents can be identified. However, identifying the root causes requires
understanding causal patterns of the accident events and causal factors. It is important to realise that the causal patterns may consist of not only single chain causation, but also may involve confluent chains as an accident could have multifactorial causes [6]. The investigation should, therefore, be designed to explore comprehensively and probe deeply various possibilities of potential causal chains rather than terminate when a chain is discovered.

To date, the pattern of accident causation is usually described by using a flowchart in which conventions of drawing the chart are determined in advance [7]. For example, events should be enclosed in rectangles and causal factors in ovals. Both the events and causal factors should be connected by arrows. The flowchart seems an ineffective method for presenting a result of investigations. A large and complex flowchart will be needed to draw confluent and branching chains of causal processes. The flowchart will be full of the rectangles, ovals, squares boxes and connecting arrows. Drawing this flowchart will take much effort. It must sometimes be presented on large drawing paper. This complexity would lead to difficulties in reading the causal process and determining the causal factors, as well as in deciding who could reasonably control accident causation. Unfortunately, there has been, as yet, no simple method other than the flowchart, for describing the causal process. An alternative tool to draw the causal process is needed instead of flowcharts. Using such a tool, investigators do not need to draw a flowchart, but only complete the causal structure with the types of accident events and causal factors they encounter.

1.2. Investigating construction accident causation

Current models for tracing causal factors of construction accidents are still confined to operative errors, unsafe conditions, and management or organisational failures generated by contractors [2], [8], [9]. In the fragmented construction project organisation, clients, the client’s team, or designers may stimulate a situation or condition to increase the risk of a construction accident. For example, the designers, through their design choices, could generate technical or operational risks, and also management or organisational risks [10]. It was also found that some cases of construction accidents could be prevented if designers put more thought into construction risks at the design stage [11]. This would suggest that an accident should be not only ascribed to operatives and builders, but also other participants, such as the designers, the client’s team, or the clients. Consequently, investigating a construction accident needs a thorough approach that allows all possible branches of the causal process of construction accidents to be revealed. The branches should not be confined to project construction, but extended into project conception, project design, as well as project environment.

Following the problems described above, a practical and rigorous model for structuring construction accident causation is needed. The structure should indicate all cause-effect relationship from which what happened and why it happened are identifiable in order to provide meaningful feedback for determining corrective actions and preventing recurrence, as well as improving construction performance. Using such a method, investigation would be much more readily undertaken to map all possible causal chains and causative factors that contribute to the accident event. The degree of contribution of a given causal factor could also be assessed. The areas of responsibility can also be delineated. Roles of people or organisations that could reasonably control the causal factors by means of elimination, reduction or avoidance of such causal factors can be identified. Having such knowledge would be of benefit in providing an effective aid to future mitigation of construction accidents.

This paper presents a CRACCA: a method of analysis of causal factors in construction accident causation. The CRACCA is acronym of Constraint-Response Analysis of Causation of Construction Accidents. It is an accident investigation model for the construction industry. Development of this model is based upon the constraint-response theory of construction accident causation developed by the authors (Suraji and Duff, 2000a). In this paper, the constraint-response theory is briefly outlined. Then, the structures and features of CRACCA are described. Finally, procedures for using this technique are also presented. In future, the technique will be complemented by an inferential method for qualifying causal factors’ contribution to construction accidents.
2. Constraint-response theory of construction accidents

2.1. Principles

The development of constraint-response theory assists in understanding construction accident causation [12]. The theory models construction accident causation in which human factors, ascribed to operatives and people at management level of a construction project organisation, are considered as fundamental factors generating accident causation [5]. In this theory, management, organisational and operational features of the construction project are modelled as a part of the causal processes of construction accidents. The theory incorporates project conception, management, design, and construction into construction accident causation. This approach assists in the analysis of contribution to, or influence of, all project participants: clients, the client’s project team, designers, and builders, as well as operatives, to increased risk of construction accident.

The fundamental concepts of the theory can be described as follows:

1. A project participant may introduce factors leading directly or indirectly to accidents. This embraces the theory of human error, that almost all factors leading to accidents arise, at least in part, from human action or inaction to eliminate, reduce or avoid accident risk. It is argued that in the behavioural approaches, root causes of construction accidents are people [13].

2. Project participants work within constraints arising from the situation of the participant’s own organisation, another project participant or the project environment. For example, clients’ decisions at project conception can introduce resource or time constraints for the designer; or a contractor can, by changing the construction sequence, produce constraints to the provision of design information.

3. A project participant’s response to such constraints will influence construction activity; for example, possibly, providing incomplete information, leading to an inappropriate construction process and increased risk of accident.

4. An inappropriate construction process would include inappropriate construction planning, control, operation, and site condition, recognising the idea of a latent failure [1]; and inappropriate operative action, often providing, in Reason’s terminology, active failure as the triggering event.

5. Consistent with domino theory of accident causation, the structure of the model creates a multiple path domino sequence in which an accident may have multifactorial causes [6].

2.2. Structure

The constraint-response theory of causal process of construction accident is modelled as a causal pattern shown in Figure 1. The model describes interrelationships among various factors of deficiency, associated with situations, conditions and operational systems of the construction process, their precursors in early project activity and its environment, and accident events as their consequences. These deficiencies are classified as inappropriate construction operation, inappropriate site condition, inappropriate operative action, inappropriate construction planning, and inappropriate construction control. These deficiencies are categorised as proximal factors, which directly increase the risk of accident. The use of the term ‘inappropriate’ rather than unsafe takes account of many factors that are not, in themselves, unsafe but some circumstances could raise the risk of accident. Precursors of these proximal factors are defined as managerial or organisational constraints experienced by project participants, and their responses to the constraints. These constraints and responses are categorised as distal factors, which indirectly to increase the risk of construction accident, by the introduction of proximal factors.
Figure 1. Generic model of constraint-response theory
3. Development of CRACCA

3.1. Objectives
The purpose of development of CRACCA is to tailor the needs of investigating causal processes in construction accident causation. As a system for conducting analyses of construction accident causation, it is also designed to be a practical tool to reconstruct causal factors of a construction accident and determine the potential or predominant causal factors leading to the construction accident. The CRACCA working model contains a generic causal network. This causal network could be of greatest value in directing the investigation. This would assist in providing meaningful inputs for prevention strategies, such as elimination, reduction or avoidance of potential factors that are likely to increase the risk of construction accident. This technique will also help to guide an effective accident investigation, simplify organisation of investigation reports, and determine the pattern of accident causation.

3.2. Descriptions
CRACCA is described as a generic framework of causal structure analysis for construction accidents as shown in Figure 2. In this model, the accident event is not structured as event tree diagrams representing an occurrence process of the construction accident but a generic causal network. The method specifically focuses on causal chain diagrams tailoring a causal process of underlying factors of an accident. The model is complemented by possible types of the accident events, proximal factors, and distal factors. These possible accident events and proximal factors have been validated. In this technique, constraints arising from project environment either social, business environment or physical environments, are incorporated into each project participant’s constraints. This will allow an analysis of project environments as described by [14] to be global factors of accidents. Although it is not easy to identify factors associated with the project environment, in this technique the environment is taken into account as distraction factors to operatives as well as other project participants [15]. In an investigation procedure, constraints from project environments would be one of the reasons of why an action or response is taken by a project participant.

Figure 2 shows the model for structuring construction accident causation. Reading the figure from right to left, the causal network represents the accident event, the general deficiency types of the construction process, constraints and responses experienced by project participants. The accident events consist of three elements: undesired outcomes (UO₁…UOₓ), ultimate undesired events (UUE₁…UUEₓ), and undesired events (UE₁…UEₓ). The general deficiency types cover five main categories of a deficient construction process: inappropriate operative action (IOA₁…IOAₓ), inappropriate construction operation (ICO₁…ICOₓ), inappropriate site condition (ISC₁…ISCₓ), inappropriate construction control (ICC₁…ICCₓ), and inappropriate construction planning (ICP₁…ICPₓ). Figure 2 also shows operatives factors and management or organisational failures by builders. Those failures are categorised as operative constraints (OC₁…OA₀), project construction constraints and responses consisting of subcontractor responses (SCR₁…SCRₒ), subcontractor constraints (SSC₁…SSCₒ), construction management responses (CMR₁…CMRₒ) as well as construction management constraints (CMC₁…CMCₒ) as direct precursors to lead to the deficiencies of the construction process. The upstream part of figure 2 represents project management responses (PMR₁…PMRₒ), project management constraints (PMC₁…PMCₒ), designer responses (DR₁…DRₒ), project design constraints (PDC₁…PDCₒ), client responses (CR₁…CRₒ) project conception constraints (PCC₁…PCCₒ).
Figure 2. Model of Causal Network of Construction Accident
The arrows represent interconnection among these causal factors and the construction accidents. These features of the model can be defined as follows:

1. **Undesired outcome** \((UO)\): the extent of consequences of an accident. It is divided into two different categories: injury to people, and damage to property. Damage to the environment would be considered, however it is rarely found in construction accidents. Injury to people is further classified as: minor injury, major injury, and fatality. Damage to property is classified as: minor damage, major damage, and destruction.

2. **Ultimate undesired event** \((UUE)\): accidents to people or accidents to property. For example: fall, struck, scaffolding collapse, and excavator overturn.

3. **Undesired event** \((UE)\): an unwanted incident immediately preceding and leading to an accident which did, or could have caused injury to construction personnel or member(s) of the general public, or damage to property or the environment as well as possible near misses. The term ‘undesired event’ is used rather than accident to avoid the frequent assumption that an accident must involve injury. Undesired events are defined as operational disturbances, or failure mechanisms, and their consequences. Undesired events can occur to any of the following disturbance of: structure, equipment or plant, ground, site service, material or component, facility, operatives or other personnel.

4. **Inappropriate operative action** \((IOA)\): improper action or inaction, either intentionally or unintentionally, by an operative which may result in increasing the risk of undesired events; e.g. carelessness or failure to adopt standard procedures.

5. **Inappropriate construction operation** \((ICO)\): unsuitable process of production of permanent or temporary works that increases the risk of undesired events; e.g. improper construction procedure or improper plant or equipment operation.

6. **Inappropriate site condition** \((ISC)\): unsuitable physical environment, in which a construction operation takes place, which may impinge on the performance of the operation and directly increase the risk of undesired events; e.g. unsuitable existing topography or unsuitable weather for the operation being undertaken.

7. **Inappropriate Construction Control** \((ICC)\): inadequate effort, either in quantity or quality, to direct or supervise the factors of construction such as to cause deviation of the construction operations from plan, and increase the risk of undesired events; e.g. inadequate control of plant or equipment operation or inadequate supervision of operative work.

8. **Inappropriate Construction Planning** \((ICP)\): inadequate analysis or formulation of the construction plan, method statement or schedule, in relation to the risk of undesired events which may lead to injury or damage to construction personnel, the general public, the property of either or the environment; e.g. inadequate method statement and inadequate structural design for temporary support structures.

9. **Operative constraint** \((OC)\): any factor, from whatever source, which may distract operatives from carrying out construction activity; e.g. social or domestic pressure or physical disability.

10. **Subcontractor response** \((SCR)\): action or inaction by the subcontractors to confront the constraints; e.g. slow down work or reallocate resources to another site.

11. **Subcontractor Constraint** \((SSC)\): similar constraints to those that confront main contractors; e.g. cash flow problems or pressure from other contracts for resources.

12. **Construction management response** \((CMR)\): action or inaction by construction managers to confront construction management constraints or problems created by the project environment; e.g. adjust level of supervision or fail to supply safety equipment.

13. **Construction management constraint** \((CMC)\): is defined as a difficulty or difficulties arising from client, project management and designer responses, or the project environment, which confront contractors during the project construction stage; e.g. short programme time scale and design variations.

14. **Project Management Response** \((PMR)\): action or inaction by the client or client’s professional team to confront an existing constraint during the project implementation stage. These are for example: increase time pressure on design team or inadequate contractor pre-qualification.

15. **Project Management Constraint** \((PMC)\): a difficulty or difficulties arising from the internal or external organisation which confront the client or client’s professional team during project
planning & design or construction phases; e.g. late delivery of design detail or limited availability of suitable contractors.

16. **Designer Response (DR)**: action or inaction by designers to confront the constraints existing during project design stage; e.g. increase design complexity or sub-let part of design process.

17. **Project Design Constraint (PDC)**: limitations or problems confronting designers during the design process. These may be stimulated by client’s responses, project management responses or the business environment of the design organisation; e.g. modified technical requirement or accelerated design programme.

18. **Client Responses (CR)**: action (or inaction) by the client in response to constraints during development of a project brief; e.g. reduce project budget or add new project criteria.

19. **Project Conception Constraints (PPC)**: constraints arising from the internal or external project environment that confront clients during the project conception phase; e.g. difficulties in obtaining funding or environmental legislation.

Furthermore, the description of CRACCA above can be exemplified by a typical crane accident as described in Suraji, Duff, and Peckitt, (2000) [Paper accepted for publication in the ASCE Journal of Construction Engineering]. Careless operative positioning and stabilising of a mobile crane leads to failure of the crane outrigger support (UE), such as sinking into soft ground, the crane overturning (UUE) and, thus, to injury of a site operative and damage to the materials being lifted (UO). It should be noted that the undesired outcomes of an accident sequence could be injury to any persons (construction personnel or members of the public), or damage to property, or the environment.

The failure to properly position and stabilize the crane is an inappropriate operative action (IOA). Lack of adequate supervision may well have been a contributing factor and would be classified as Inappropriate Construction Control (ICC). In the event that the crane was not suitable for the operation being attempted because, for example, its outrigger could not have reached stable ground, then this factor would be classified as Inappropriate Construction Operation (ICO). This may have arisen as a result of ground conditions surrounding the operation, which were unsuited to the use of a mobile crane, one of the factors classified as Inappropriate Site Conditions (ISC). The failure to recognize this situation is often caused by inadequate site investigation by the contractor, a factor classified in the model as Inappropriate Construction Planning (ICP).

The third, and often ignored, area of focus of the methods represents the distal factors, the constraints and responses upstream of the immediate event area that create the situations in which the proximal factors are generated. In the complete method, the distal factors and their relationships are developed to show the influence of the client, the design team, and the project management team, as well as recognizing the specific influence of subcontractors in the construction management process.

The client will be under a number of economic, social and political pressures, in the conceptual development of the project, which we call **Project Conception Constraints (PCC)**, and these will provoke **Client Responses (CR)** in the development of the project brief to the project management and design teams. These responses will provide many of the constraints, **Project Management Constraints (PMC)** and **Project Design Constraints (PDC)**, within which the project management and design participants have to operate. Their responses will, in turn, provide **Construction Management Constraints (CMC)**, within which the construction process will take place. These will provoke responses from **Construction Management Response (CMR), Subcontractor Constraints (SCC) and Subcontractor Responses (SCR)**. This cause and effect process has the potential to increase **Operative Constraints (OC)** and directly, or indirectly through **Inappropriate Construction Planning (ICP)** or **Inappropriate Construction Control (ICC)** procedures, lead to the **Inappropriate Site Conditions (ISC), Inappropriate Operative Action (IOA) or Inappropriate Construction Operation (ICO)**.

### 3.3. The use of model

Investigators may use CRACCA to guide and structure investigation procedures. The investigators can classify the investigation procedures into four sections. In the first section, the investigators collect facts of types of undesired outcomes, ultimate undesired events, and undesired events. These three elements of an accident event can be presented as a first part of causal networks. In the second section, the investigators probe deeply to identify possible deficiencies of the construction process. In the first instance, the investigators may look into inappropriate operative actions, followed by
examination to determine whether any inappropriate site condition and inappropriate construction operation is involved. While asking why these two deficiencies occurred, the investigators may search for the answers to this question by analysing construction planning and construction control, whilst the answers to why the inappropriate operative actions occurred are answered by investigating operative constraints.

The third section of the investigation answers the question as to why those inappropriate construction planning, construction control, and operative constraints arose within the construction process. This would lead to the investigation of management or organisational aspects of the builders. The investigators may need to probe thoroughly into a subcontractor’s or main contractor’s management constraints and responses (project construction constraints and responses) that lead to failures to provide reliable construction planning and control. However, in the case of investigating why the operative constraints occurred, the inappropriate construction operation and inappropriate site condition should also be evaluated for possible having influences on the operative constraints.

Finally, the fourth section is directed to deal with the upstream boundary of project construction. It suggests that the investigators look into relevant factors related to project design, project management and project conception. Firstly, the investigators may explore possible design constraints and designer responses that would generate the project construction constraints and responses. Secondly, the investigation is directed to reveal project management constraints and responses by other client’s team, such as project managers, quantity surveyors, or planning supervisors. Finally, client responses and project conception constraints are investigated. In this procedure, project environment constraints are not specifically addressed due to the fact that constraints are incorporated into the project participants’ constraints. All those identified causal factors are then reconstructed into a causal network of construction accident according the model (Figure 2).

4. Conclusions
Construction accidents may involve various causal factors. A structured investigation method is needed to map the root cause of the construction accident. A constraint response analysis of causation of construction accident (CRACCA) is developed as a model for structuring causal factors of construction accidents. This model is intended as a practical method of investigation tailoring various causal factors in construction accident causation. Development of the method is based upon the constraint-response theory. This theory embraces many features of management or organizational factors, operational aspects, and accident events in the construction project organization. As a practical investigation tool, the CRACCA provides a useful guide for investigators to analyse construction accidents in detail. The investigators do not need to draw any diagram, such as event tree or fault tree diagram. They only investigate facts from accident events, matching them to the proximal factors or distal factors provided and then plotting these causal factors into the model.

5. References
[1]. Reason, J. The contribution of latent human failures to the breakdown of complex systems. in Broedben, D. E., Baddeley, A., Reason J. T. 1990. Human factors in hazardous situations, proceeding of a royal society discussion meeting, Oxford Science Publications, Oxford.
[2]. Whittington, C., Livingston, A., Lucas 1992, DA Research into management, organisational and human factors in the construction industry, HSE Contract Research Report No. 45/ HMSO,
[3]. Bellamy, L. J. & Geyer, T. A. W 1992. Organisational, management and human factors in quantified risk assessment, HSE Contract Research Report No. 33, HSE, London.
[4]. Groeneweg, J 1994, Controlling the Controllable: The Management of Safety, 2nd Revised Ed. DSWO Press, Leiden University, Netherlands.
[5]. Suraji, A and Duff, A. R 2000. Constraint-response theory of construction accident causation, Proceeding of International Conference on Designing for Safety, CIB Working Commission W99-European Construction Institute, London, UK, June.
[6]. Petersen, D 1971, Techniques of safety management, McGraw-Hill, New York.
[7]. Johnson 1990, W.G. MORT: The management oversight and risk tree, Journal of Safety Research, March.
[8]. Embrey, D 1992, Incorporating management and organisational factors into probabilistic safety assessment, Reliability Engineering and System Safety, 38, 199-208
[9]. Abdelhamid, T.S 2000, and Everett, J.G., Identifying root causes of construction accidents, Journal of Construction Engineering and Management, 126 (1), 52-60.

[10]. Suraji, A and Duff, A.R., Incorporating site management factors into design for a safe construction process, Proceeding of International Conference on Designing for Safety, CIB Working Commission W99-European Construction Institute, London, UK, June, 2000.

[11]. Maitra, A 1999, Designers under CDM- a Discussion with Case Studies, Proceeding of Institution of Civil Engineers, Civil Engineering, Vo. 132, Issue 2/3, May/August, pp: 77-84

[12]. Suraji, A 2001 Duff, A.R., Peckitt, S.J. Development of a causal model of construction accident causation, Accepted for publication in the ASCE Journal of Construction Engineering & Management [in print].

[13]. Duff, A.R. Management and operative safety: a Goal for the whole organisation, Proceedings of the International Conference on Environment, Quality and Safety in Construction, CIB Working Commission W99-Safety and Health on Construction Sites, Lisbon, Portugal, June,1998.

[14]. Atkinson, A 1998 Human error in the management of building project, Journal of Construction Management and Economics, 16, 339-349

[15]. Hinze, J., The distraction theory of accident causation, Proceedings of the International Conference on Implementation of Safety and Health on Construction Site, CIB Working Commission W99-Safety and Health on Construction Sites, Lisbon, Portugal, September, 1996.