Identification and Quantification of the Causes of Construction Defects

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Abstract. Construction defects do not usually occur due to the impact of a single cause, but rather occur when multiple complemented causes combine, forming a defect's recipe. While there are numerous recipes in which a defect may result, the importance of causes vary in term of the number (i.e. frequency) of recipes in which they take a part of, and the size (i.e. magnitude) of contribution they provide for the formation of these recipes. So far, there is still a lack of research that quantifies the risk of these complex causes so that more efficient defect management strategies are developed. Accordingly, this study develops a fault-tree for formulating the structure of the complex causes resulting in defects; and conjunctionally utilizes risk importance measures to quantify the influences of defect causes from two main criterions: frequency and magnitude.

Keywords: Defect, Rework, Failure, Error, Risk

1. Introduction

Construction defects can yield severe consequences including rework, schedule delay, cost overrun, claims and disputes [1]. It is not usually an outcome of a singular variable's impact, but rather occurs when multiple complemented causes combine [2]. For example, worker's *lack of skill* alone may not cause a defect, unless combined with *inadequate supervision* of site engineers who are responsible of correcting workers mistakes. Similar to these two complemented variables, there are numerous recipes in which the defect may result. Each of these variables is also analogized a 'hole' that weakens the defence layers of the system and increases the possibility of a defect to find its way to existence [3]. According to Reason's 'Swiss Cheese Model' [3], holes could be found in any of the four descending defence layers: *Organizational Influences, Defective Supervision, Preconditions for Defective Acts and the Defective Acts*. Once complemented holes meet together, a defect consequently penetrates and comes to light. While there are numerous pathways in which a defect could penetrate, holes vary in terms of the number of pathways it takes a part of, and the size of access it provides for such penetrations (refer to Figure 1). For example, the issue of workers *lack of skill* would form the largest hole in the system when it appears to be the major cause among the other complemented ones. Thus, its existence mostly jeopardizes the system. In contrary, the *inadequacy of supervision* would form a smaller hole in the system when it appears to be a minor cause of defects. However, if such a small hole takes a part of all possible pathways that lead to a defect, then its importance centralizes upon its capability of not allowing any of the defect pathways to continue its journey. This highlights the fact that the influences of variables vary, not only in terms of magnitude, but also in terms of frequency. By referring to the representation illustrated in Figure 1, one could briefly remark how the importance of holes differs. Such difference emphasizes the necessity of understanding the complexity of defect causes and characterizing the influence of each variable. Once this information is obtained, a more efficient defect prevention strategy could be developed. For instance, project participants may not always have the capability of blocking all holes that lead to a defect, but rather need to minimize defect's risk by identifying the most important holes and removing them. Furthermore, if a holistic defect prevention plan is to be made, project participant may prefer ranking the importance of these variables in order to prioritize managerial efforts. Accordingly, this study aims to provide a means for quantifying the influence of defect causes. For this, we will examine the applicability of fault-trees for modelling the complexity of defect causes. Conjunctionally, we will examine the utility of risk importance measures (IMs), provided by risk and

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safety engineering literature, to characterize the influence of each cause from two criterions: magnitude and frequency.

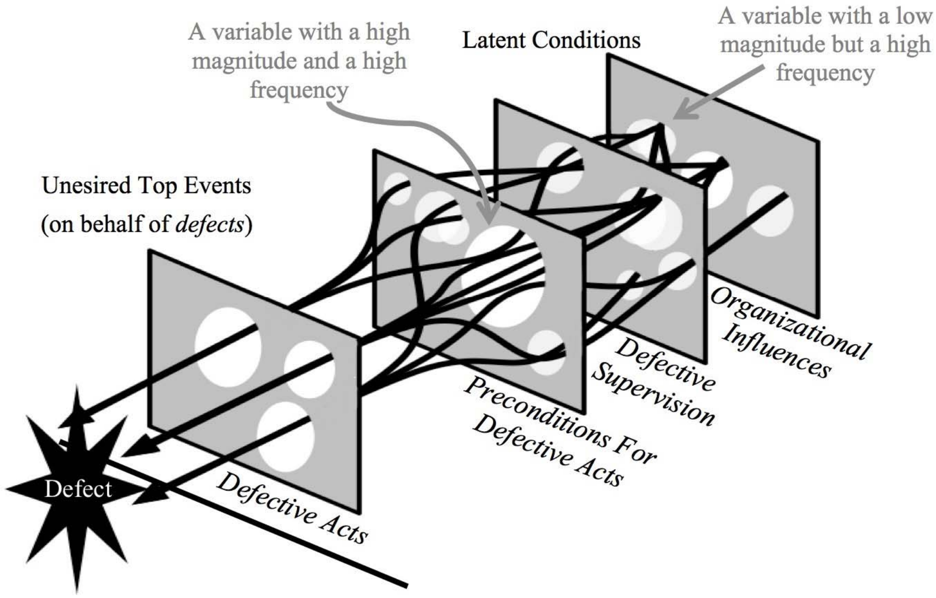

Fig. 1. A visual representation of the Swiss Cheese Model, showing how a defect could find its way through various combinations of variables, analogized as 'holes'.

2. Literature Review

By referring to the Swiss Cheese Model, there is a consensus settling among academics that the correction or elimination of root causes (i.e. 'holes' found at basic levels) shall spontaneously prevent defects from occurring [4]. Accordingly, several authors strived to identify them. Yet, an issue raised with the strategy of *merely* identifying root causes, is that it lacks a clear identification of the mechanics and complex correlations acting among variables in between, which thus makes it less explanatory; furthermore, comprehending these root causes is not guaranteed since their association with the up-front incidence is not clearly visualized [1]. Alternatively, it was suggested to track root causes through a 'bottom-up' approach, so that investigations initiate from the 'most direct' up to those 'most basic' causes. The most direct causes herein are called 'defective acts' [1], which were defined as individualistic erroneous practices that are formalized either in terms of human errors or violations. Since the removal of these conditions (lying at the final defence boundary in a system), also, have the capability of preventing defect, investigations could therefore centralize on 'defective act' as *the* undesired top event, on the behalf of defect (Fig. 1). Accordingly, Aljassmi and Han's [1] nine defective act classifications could be utilized as a platform towards investigating root causes (i.e. latent conditions). These classifications are presumed to comprehend the undesired top events that yield to defects in residential projects [1], and consist of the following: *Poor workmanship; Impaired material usage; Task sequence omission; Deviation from an intended dimension; Instruction contravention; Professional principles/conventions noncompliance; Official rule noncompliance; Items interdependence disregard* and *Adoption of misguiding instruction*.

3. Methodology

Once the defective acts are identified, investigations could accordingly centralize towards addressing the complex root causes that underlie their existence. In this research, a fault tree approach is utilized in order to identify possible and potential latent conditions and their complex effect on a defective act. The rationale behind proposing it herein is due to its capability of aggregating all possible combinations of latent conditions that trigger a defective act, to form a unified predictive risk model. Such combinations of latent conditions could be normally found when investigating numerous instances of a particular defective act. In principle, the bigger the sampled defective act instances, the more accurate the fault-tree becomes in predicting pathways that lead to its occurrence. The fault-tree consists of three main composites (illustrated in the Figure 2): *basic events* (latent conditions), *subsets* (a sampled defective act instance, which consist of a combination of intersecting latent conditions), and the *top event* (the investigated defective act). Whereby, latent conditions that intersect to trigger an instance are articulated through AND gates (represent the multiplication rule of probability); and all possible defective act instances are articulated through OR gates (represent the addition rule of probability). In theory, this means that the top event (defective act) will function if any of the given subsets (consisting of possible complemented latent condition combinations) function. In terms of the Swiss Cheese model [3], *events* could be viewed as the circumstance of passing the 'holes' that lay within the three primary defence layers: *Preconditions for Defective Acts, Defective Supervision and Organizational Influences*; and *subsets* could be viewed as the instances where a defect risk has penetrated through these holes to the defective acts defence layer (i.e. the final layer prior to defect).

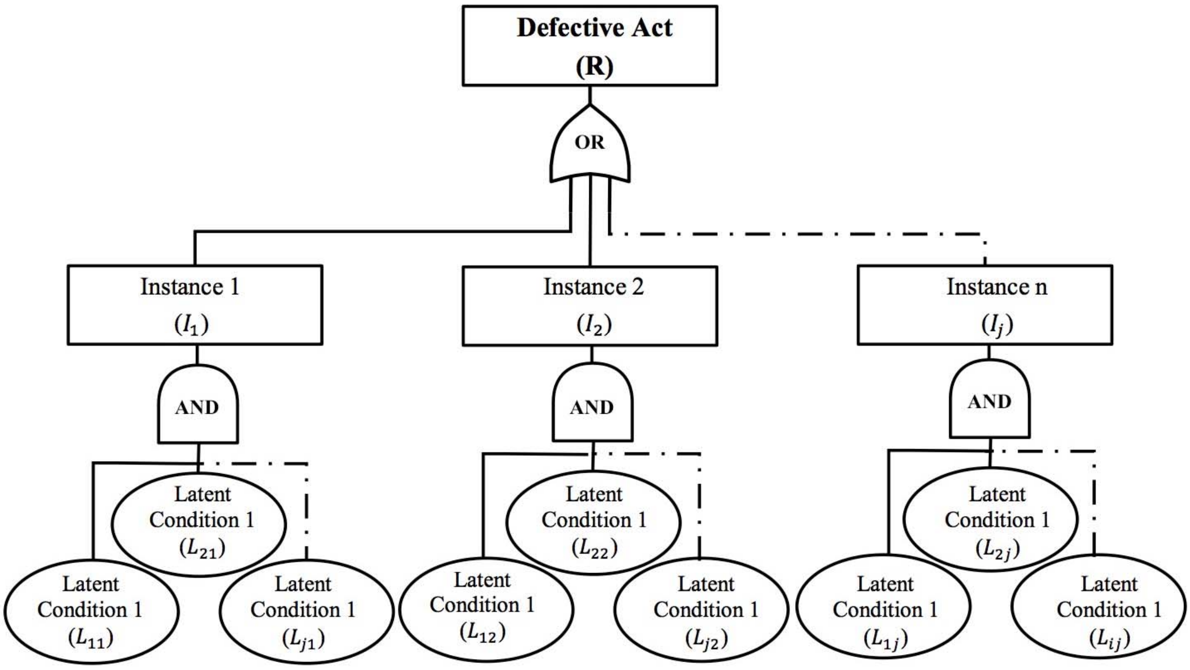

Fig. 2. The proposed fault tree composites, where latent conditions are articulated through AND gates (representing the multiplication rule of probability) and the sampled instances are articulated through OR gates (representing the multiplication rule of probability).

3.1. Fault-Tree Construction

As a base for constructing the fault tree, the risk of the top-event (*R*) will be set to unity (one).

$$R_0 = \sum I_j = 1$$

Where:

I_j = The probability of an instance.

R = The overall defective acts' risk.

The overall risk value will thence be divided equally among the subsets, assuming that all subsets (i.e. sampled instances) have an equal probability to cause a defective act:

$$I_j = \frac{1}{n}$$

On the other hand, latent conditions within a particular subset *I* do *not* necessarily have an equal probabilistic value (*L*), although their product should always equal to 1/*n*. This is a critical aspect of the risk model construction, which will be further discussed.

$$I_j = \prod_{i=1}^{m} L_i = \frac{1}{n}$$

Noteworthy, basic events could alternatively be represented in a general matrix, for a convenient notational system, as suggested by Iman [5].

$$[L_{ij}] = \begin{bmatrix} L_{11} & L_{12} & \cdots & L_{1n} \\ L_{21} & L_{22} & \dots & L_{2n} \\ \dots & \dots & \dots & \dots \\ L_{m1} & L_{m2} & \dots & L_{mn} \end{bmatrix}$$

Where:

L =Probabilistic value of a letent condition (i.e. an event).

m = Number of <u>all</u> identified Latent Conditions in the model (i's row).

n = Number of sampled defective act incidents (j's column).

The model construction described above is contingent upon setting the overall risk value to 1 and instance probabilities to $1/n$, forming a headwater for all latent condition parameters. Therefore, the critical aspect of the risk model is to distribute these parameters according to latent conditions' influence on their provoked instance. Therefore, a practitioner who is well informed about the project system's conditions could assess each latent condition's influence according to a 1-5 rating (s), which could also be represented as a Likert scale. Consequently, square 1/n by the ratio of each latent condition's raring with the overall ratings' sum. This should proportionally attribute the probabilistic values of each latent condition according to their influence (note that latent conditions with high influence shall technically obtain a lower probabilistic value and *vice-versa*).

$$L_{ij} = \left(\frac{1}{n}\right)^{\frac{s_{ij}}{\sum_{i=1}^{m} s_{ij}}}$$

To sum up, the overall risk equation could be expressed as:

$$R_0 = \sum_{j=1}^{n} \left(\prod_{i=1}^{m} \frac{1}{n}^{\frac{s_{ij}}{\sum_{i=1}^{m} s_{ij}}} \right) = 1$$

3.2. Risk Importance Measures

All The model construction described above aims to distribute probabilistic parameters so that the overall risk R_0 equals unity (one) at all times. The primary objective underlying this is to establish a reference where latent conditions' importance is compared with each other. In this regards, risk Importance Measures (IM's) are used to quantify the significance of a latent condition. Several IMs are available whilst each contains different information, and therefore has its own use [6]. One common feature amongst IMs is that they all account in their equations the overall risk R state when a latent condition is *critical* (i.e. set to 1 or 0). Note that these IMs are traditionally aimed to measure a singular basic event ij at a time. However, the concern in this study is the integrated importance of multiple basic events (i.e. found in multiple js) that consist a particular latent condition i. This could be achieved by dealing with the evaluated latent condition i group (e.g. $L_{i1}, L_{i2}, L_{i3}, L_{i4}, L_{i5}...L_{ij}$) as a singular measure parameter L_i.

By reviewing IMs provided in risk and safety engineering literature, we suggest that Birnbaum Importance (BI) and Fussel-Vesely (FV) measures are sufficient for characterizing the importance of latent conditions (Table 1). We use BI as an indicator of a latent condition's *magnitude* and FV as an indicator of a latent condition's *frequency*. Latent conditions with a high magnitude are those that mostly jeopardize the system, since the occurrence of a defective act is most sensitive to its existence. On the other hand, latent conditions with a high frequency are those that contribute to a large number of possible pathways leading to the defective act. Thereby, the importance of high frequency latent conditions centralizes upon their capability of blocking a high number of possibilities in which a defective act results, no matter how small or large they are. The difference between latent conditions' magnitude and frequency (although magnitude is technically affected frequency) highlights the fact that managers could adopt different strategies for responding to defective acts.

TABLE 1: Proposed Risk Importance Measures (IMs)

Measure	Abbreviation Principle
Birnbaum Importance (BI)	$R_i^+ - R_i^-$
Fussel-Veseley (FV)	$\frac{R_0 - R_i^-}{R_i^-} = 1 - R_i^-$
R_i^+ = Overall model risk with the probability of latent condition L_i set to 1 R_i^- = Overall model risk with the probability of latent condition L_i set to 0 R_0 = Base value of the defective act risk (=1 at all times in this study)	

4. Concluding Summary

The difference between latent conditions' magnitude and frequency (although magnitude is technically affected frequency) highlights the fact that managers could adopt different strategies for responding to defective acts. For instance, if management's priority is to devote efforts for which latent condition's removal will yield the most effective improvements to the system's immunity toward defective acts, then *magnitude* quantification should prevail. On the other hand, if management's priority is to devote efforts for which latent condition's removal most prevents the defective act, regardless the extent of system improvements, then *frequency* rankings should prevail. Results from this study reveal that removing those high frequency root causes do not necessarily yield to significant improvements on the system's immunity toward defects. Therefore, both criterions must be considered for an efficient characterization of latent conditions.

The methodology introduced in this study could be used as an investigation tool for modelling and characterizing the complex variables resulting to defects in residential, industrial or commercial projects.

5. References

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