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## Shainin's Experiment Design Methodology in Occupational Safety Assessment: Application Guidelines

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**Abstract:**

**Purpose:** The article refers to the role of safety management measures and their significance for reducing the cost of accidents, injuries and diseases and costs resulting from disruptions of manufacturing processes, that are borne by employers. It is shown that for any improvement measures to be effective, it is vital to ascertain the nature of defects, the circumstances in which they occur and to eliminate their root causes.

**Design/Methodology/Approach:** The article outlines the potential for assessing occupational safety by means of Shainin's experiment design methods. It shows that the experiment techniques can be used to identify and assess problems with sufficient accuracy helping organizations to identify adequate process improvement measures. It enumerates the key prerequisites for the use of Shainin's experiment design method and describes a relevant procedure that ensures the achievement of desired outcomes.

**Findings:** A review of relevant literature shows that Shainin's experiment design methods, which were originally developed to improve manufacturing processes, can be used to address issues in the production working environment.

**Practical implications:** A procedure is developed for identifying key disruptions which, if eliminated, will improve working conditions and worker well-being. Examples are provided of the factors to be targeted to achieve the desired improvements in the working environment. In this manner, the study can help organizations choose and roll out adequate solutions that will suit their methodologies and lead to desired outcomes. The proposed procedure supports the identification of the working environment factors that significantly affect safety, and helps define their impacts and, consequently, improve the effectiveness of improvement measures.

**Originality/Value:** While the article stops short of offering an example of the procedure, it points to the implications of experiments that are helpful in reducing occupational hazards. In the field of occupational safety, the article shows the potential of employing Shainin's experiment design method to examine any well-defined issue and any issue having to do with the manufacturing environment and the conditions required for the safe operation of workers.

**Keywords:** Shainin's experiment design methodology, occupational safety, workplace, working environment improvements, selection of improvement measures and actions.

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## 1. Introduction

To ensure that work is performed safely, organizations need to design and monitor their processes adequately. It is vital that they consider all variables in the environment that either positively or negatively impact on their processes (Górny, 2019; Marczevska-Kuzma, 2021). By monitoring their processes, they can reduce adverse impacts on both the worker and the working environment and ensure positive impacts to their benefit. A possible safety standard would be not to exceed permissible workloads. This applies to both the working environment and work performance parameters. To reduce such negative impacts, manufacturers are advised to identify hazards and untoward factors that may adversely affect process operators, i.e., workers.

The working environment should be recognized as part of the environment that determines the way that production processes are conducted. This environment should be viewed by reference to the criteria whose satisfaction is paramount to enabling workers to carry out their tasks (Górny, 2020; Mościcka-Teske, 2017; Rut *et al.*, 2021). Many hazards and untoward factors that need to be monitored and reduced relate to processes. All processes can potentially result in defects.

Due to their complexity, which makes reliable assessments more challenging, it is crucial to use tools that help identify problems, define their characteristics, and support the selection of adequate improvement measures. Such measures must account for the nature of any defects and the severity of their impacts on workers. A secondary consideration is the choice of an assessment method to inform effective improvements.

Shainin's approach is considered a simple experimental method used for quality improvement. One of its distinctive features and main advantages is the absence of interference in the processes being assessed (Pankaj, *et al.*, 2020). Shainin's experiment design methodology allows one to identify process disruptions and select improvement measures.

In assessing occupational safety in production, Shainin's experiment design methodology has the potential to help identify problems and select adequate process improvement measures (Pankaj *et al.*, 2020). In assessing manufacturing safety, it is vital to isolate the causes of hazards and untoward factors. Based on the assumption that problems result largely from disruptions generated by machinery, equipment, instruments, and other work factors that are necessary for production, it is possible to define their beneficial and adverse impacts on worker safety.

## 2. Scope of Experiments Determined by Hazards and Findings of Occupational Safety Assessments

Hazards in the working environment vary widely in their nature. They include:

- Chemical hazards caused by harmful chemical compounds in the form of liquids, gases, dusts, fumes and vapors having a toxic effect on workers. Chemical hazards

result from the use of the above substances in processes, their production and processing, and/or their presence in the working environment,

- Physical hazards in the form of noise, vibrations, thermal factors (oppressive temperatures), radiation, etc., which are commonly associated with hazards in the working environment posed to worker health and factors that reduce working comfort. Their deleterious impacts are typically a consequence of direct exposure.
- Biomechanical hazards resulting from specific forms of manual work and work postures, most biomechanical problems are caused by repetitive motions, static work postures and considerable untoward physical factors.

In identifying and assessing hazards, due account should be taken of their nature. The factors that occur in the working environment vary widely in their nature. At any given time, workers may be exposed to multiple occupational hazards, which may increase the risk of suffering from adverse health effects. A proper assessment of such hazards requires an analysis of the impact of repeated occupational exposures to any chemical, biomechanical and/or physical factors that may generate adverse health effects in workers.

To improve occupational safety, it is essential to identify the dominant factors that adversely affect workers' ability to operate in the working environment. Such factors will guide the scope of improvements necessary to boost occupational safety (Janackovic *et al.*, 2020). The improvements can be classified as organizational, technical, and human-related (Itani, 2011; Kariuki and Lowe, 2007). Such factors determine safety levels, worker error rates, work-performance-related risks and the effectiveness of improvement measures and workflow modifications.

For most accurate results of problem assessments, it is advisable to use quantitative methods that unambiguously identify the nature of issues at hand. Quantitative working environment parameters will describe the state of the working environment and can be used to support effective task performance by workers. Assessment results may include simulations, ratings of problem severity and basic areas for improvement.

Organizations must recognize the importance of achieving and subsequently maintaining the kinds of working conditions that will enable their workers to perform their work safely. The sheer number, quality, and prominence of studies available in this field clearly show the significance of this matter (Castillo *et al.*, 2020). Safe workplaces should be seen as a primary prerequisite for the proper performance of work. The creation of safe working conditions is integral to a company's core business (Tsalis *et al.*, 2018). Therefore, in both manufacturing and service operations, considerable emphasis should be placed on safety measures, especially where such measures manifestly improve the bottom line.

Appropriate working conditions are necessary for worker well-being and therefore also for their effective functioning (De Cieri and Lazarova 2020; Ji *et al.*, 2020). Ensuring safety is the first step towards that goal. In addition, sustainably safe and good working

conditions should be seen as a key resource in any organization (Fernández-Muñiz *et al.*, 2018; Rut *et al.*, 2021).

It is therefore crucial to identify any excessive exposures to hazards and either effectively eliminate or mitigate them (Sutton, 2015). The assessment of physical and chemical hazards is the first step towards proper risk management in any industry (Papazoglou *et al.*, 2017). Accurate standardized measurements are fundamental for assessing the types and quantities of hazardous substances found in the working environment and estimating the severity of hazards. Most today's studies on occupational hazards focus on resolving issues encountered in the application of preventive and control measures.

### 3. Shainin's Method of Experiment Design

Since quality can be described by reference to a set of attributes, the quality of an object can be described by specifying the attributes of that object (Hamrol, 2005; Pankaj *et al.*, 2020; Rauwendaal, 2019). In describing the quality of the working environment, use can be made of a set of attributes that characterize the space in which workers operate and perform their tasks. Such attributes determine their ability to effectively perform their assigned duties. The main goal of this exercise is to identify variables that potentially cause deviations from the desired state. To simplify the procedure, any irrelevant variables that may distort the research procedure should be omitted.

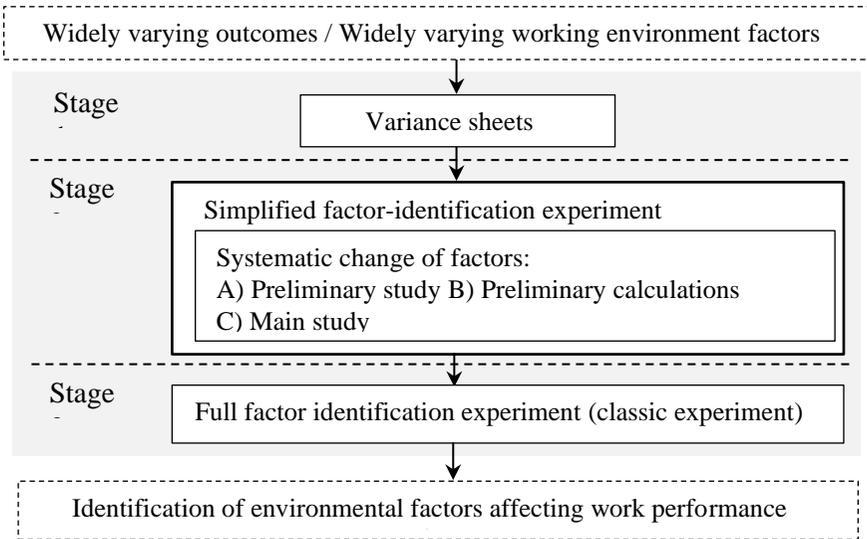
Shainin's classic experiments are a simplified method used to design processes for best performance quality. The research presumes that it is essential to ensure a working environment that will keep the workers safe from accidents, be worker friendly and ensure their working comfort. The method is designed to (Hamrol, 2005; Pankaj *et al.*, 2020; Rauwendaal, 2019):

- Isolate the controllable factors that have the strongest impact on process quality,
- Isolate the controllable factors that most effectively reduce quality variances,
- Determining the optimal controllable factor settings to obtain the required quality of process outputs and maximum process resilience to disruptions,
- Identify the factors that have a minimal (negligible) impact on process quality and determine their recommended values based on economic criteria.

One distinctive feature of Shainin's experiments is the gradual elimination of the factors that are being examined (Rauwendaal, 2019). Shainin's technique helps reduce variance by 70% by eliminating causes of adverse impacts. Such reductions are achieved at every step of the process. The result are 2 to 4 identified dominant factors. The ultimate number of factors is sufficient to conduct a full experiment. As part of the full procedure, experiments are carried out for all dominant factors. When analyzing the results, it is also possible to account for mutual interactions among the factors (Belavendram, 1995; Hamrol, 2005). The greatest advantage of Shainin's experiment design method is the ability to perform the analysis solely based on information that constitutes an external description of the process (Belavendram, 1995). This means there is no need to interfere with process flows.

A short procedure relying on Dorian Shainin's experiment techniques is presented in Figure 1. The diagram shows the option of using the methodology to analyze factors that describe a working environment. Such factors determine work performance safety. Significant steps in such experiments are distinguished as Stages 1, 2 and 3.

**Figure 1.** Assessment by Shainin's experiment design method, including an assessment of the impact of working environment variables on the safe performance of work



**Source:** Author's research.

The procedure presented in Figure 1 is one of many possible options. In the simplest case, the results of the first stage of experiments may narrow the number of controllable factors down to a handful that may be seen as dominant or show that none of the factors affect process outputs (Belavendram, 1995). This will allow one to skip Stage 2 and proceed directly to Stage 3 of the assessment.

In a full study based on Shainin's experiment design methodology, three basic stages should be followed (Hamrol, 2005; Pankaj *et al.*, 2020; Khavekar *et al.*, 2018).

**STAGE 1:** Variance sheets are used to identify key factors affecting process performance and examine measurable factors. The assessment accounts for variances over time in working conditions factors. To obtain the required information, variance sheet users should take note of their characteristic features and requirements. Within their basic scope, variance sheets show variation (or the lack thereof):

- During process performance (e.g., during the performance of individual tasks, depending on equipment, process parameters and task nature),
- That occurs cyclically, regardless of process performance (e.g., variance across product batches and/or tasks performed),
- Is a function of time or another process parameter (e.g. parameters of work).

The use of variance sheets allows organizations to significantly reduce the number of factors used to describe process variance. This is typically achieved by identifying the dominant variance factor and associating with it factors that require special attention in process design. A prime determinant of a successful outcome is resilience to process disruptions.

In assessing occupational safety, such factors significantly determine the occurrence of hazards and untoward factors helping one to reduce their prevalence by removing or eliminating the underlying causes of hazards and untoward factors. To obtain full information about hazards and untoward factors, an organization needs to identify process disruption risks in detail. Stage 1 may be affected by the causes of hazards and untoward factors and the nature of their impacts.

**STAGE 2:** Systematic change in factors. The systematic change in factors is an assessment stage designed to identify factors having the strongest impact on selected process attributes (Khavekar *et al.*, 2018).

Assessments of systematic factor change are comprised of three basic sub-stages:

- a) Preliminary study,
- b) Preliminary calculations,
- c) Main study.

**SUB-STAGE 2A:** The preliminary study involves an assessment of controllable factors known to have the greatest impact on process output. Typically, the assessment covers factors identified by examining the process with the use of variance sheets. The number of factors examined in this manner ranges from a few to over a dozen.

The characteristics observed are described by reference to states, which are used to identify:

- the controllable factors that affect the process at hand (denoted as  $X_i$ ),
- processes affected by given controllable factor (denoted as  $Y_i$ ).

The above relationship should apply to all identified controlled factors (denoted as  $i$ ). Each identified factor may assume either of the following two states:

- $X_{i+}$ : factor presumed to have beneficial impact on process output  $Y$  (characteristics),
- $X_{i-}$ : factor presumed to have adverse impact on process output  $Y$  (characteristics).

The two preliminary experiments are conducted on the assumption that:

- All selected factors are set to be theoretically “adverse”, denoted as  $X_-$ ,
- All selected factors are set to be theoretically “beneficial”, denoted as  $X_+$ ,

Each experiment should be performed multiple times, preferably in random order.

**SUB-STEP 2B:** Preliminary calculations are performed to obtain the input data needed to conduct the main study.

Such preliminary calculations include:

- A calculation of the mean value of a given attribute for each experiment,
- A calculation of difference D between mean values from a pair of experiments,
- A calculation of ranges from iterations of each experiment,
- A calculation of the mean range R from a pair of experiments,
- A check of the significance of the difference of mean values conducted by determining ratio  $q = R/D$  and its comparison with the criterion value:
  - If  $q < 1.25$ , the cause of the variance is assumed to be the inherent process variance or the impact of unaccounted for factors, i.e. such variance cannot be explained by the impact of factors  $X_i$  tested in the experiment. This means that a different set of factors should be selected for examination or that the process should be considered to be either uncontrollable and in need of a fundamental structural change,
  - If  $q \geq 1.25$ , the cause of the variance is assumed to be the process factors that are tested at this stage of the procedure, meaning it is possible to proceed to the next stage of the calculation,
- A calculation of control lines for the process with all factors  $X_{i+}$  and for the process with all factors  $X_{i-}$ :

$$UCL (LCL) = Y_{\text{mean}} \pm u_{\alpha/2} \cdot \frac{\hat{\delta}_{\text{exp}}}{\sqrt{r}} \quad (1)$$

where:

$Y_{\text{mean}}$ : mean value for either process  $X_+$  or  $X_-$ ,

$u_{\alpha/2}$ : the quantile of the normal distribution (it is recommended to assume that  $\alpha = 0.0027$  (Hamrol, 2005),

$\hat{\delta}_{\text{exp}}$ : standard deviation determined by Hartley's formula:

$$\hat{\delta}_{\text{exp}} = \frac{R}{d_2} \quad (2)$$

R – output range in either process  $X_+$  or process  $X_-$ ,

$d_2$  - Hartley's coefficient dependent on sample size and sample number, used as a basis for calculating range R,

r – number of iterations in the main study.

The upper and lower control limits (UCL, LCL) are referred to as response-trigger limits. If an examined factor exceeds these lines, the relevant process requires an adjustment (Hamrol, 2005; Khavekar *et al.*, 2018). The adjustments reduce the range of values.

**SUB-STAGE 2C:** The main study is conducted to identify the smallest possible number of factors that affect a process.

The main study includes:

- Assuming that factors  $X_i$  are positive (-) and that all other factors P are negative (+),

- An experiment and check of the position of attribute  $Y(X_i P_+)$  relative to the control limits,
- Repetition of the experiment with result  $X_i$  set at (+) and the remaining factors  $P$  set at (-) to obtain result  $Y(X_{i+} P_-)$ .

The results are then plotted on a chart followed by a determination of their position relative to the control limits separately for each process driven by factors  $X_+$  and  $X_-$ . An analysis of the results points to the following (Hamrol, 2005):

- If both results, i.e.,  $Y(X_i P_+)$  and  $Y(X_{i+} P_-)$  lie in the area delimited by the control limits, the impact of factor  $X_i$  (and all possible combinations of factors related thereto) will be insignificant,
- If the result (e.g., for  $Y(X_i P_+)$ ) changes completely producing a result similar to that for  $Y(X_-)$ , and if the result for  $Y(X_{i+} P_-)$  is similar to that for  $Y(X_+)$ , factor  $X_i$  should be recognized as significant and as one that is responsible for all process variance. Thus, all remaining factors can be deemed to be insignificant,
- If both results  $Y(X_i P_+)$  and  $Y(X_{i+} P_-)$  lie outside of the area delimited by the control limits, but are not responsible for the entire variance, a possible conclusion is that factor  $X_i$  (and all possible factors associated therewith) are significant and that an additional full experiment is necessary to fully explain its meaning.

For a complete assessment, it is necessary to examine the interaction again and test all selected factors  $X_i$ . For a reliable, quick, and effective assessment of occupational safety, it is advisable to select factors that can be assumed to significantly affect working conditions. Examples of such factors are provided in Table 1.

**Table 1.** Examples of working environment factors associated with working conditions to be tested in Shainin's experiments

Factor code	Factor considered	Theoretically positive (+) factor	Theoretically negative (-) factor
X <sub>1</sub>	Noise generated when working an incorrectly clamped workpiece	Noise does not exceed limit value	Noise has detrimental and disruptive effect on worker
X <sub>2</sub>	Vibrations generated by operating a device	Vibrations below permissible value of general and local	Vibrations having detrimental effect on worker health
X <sub>3</sub>	Dust produced as a by-product of the manufacturing process	Weighted mean dust concentration does not exceed occupational exposure limit applicable to free crystalline silica	The dust either adversely affects worker respiratory system or enters worker's body through other routes; it also adversely affects process performance
X <sub>4</sub>	Device efficiency (including safety measures)	Technical measures selected accordingly to the required risk level, with due account taken of the adverse impact on	The technical measures fail to ensure complete safety in task performance, particularly where the operating parameters of a

		workers and process performance	device deviate from desired or assumed levels
X <sub>5</sub>	Physical and mental loads in device operation	Loads do not exceed permissible values, enabling workers to operate properly in working environment	Physical loads are excessive and exceeding recommended levels. Workloads result in excessive mental pressures
X <sub>6</sub>	Professional training and competencies of workers	Workers have the required training and competences to perform work, proven with relevant certificates	Workers do not have the knowledge and skills necessary to safely perform their tasks

*Source: Author's research.*

**STAGE 3:** Classic experiment (full factorial experiment). The classic experiment determines mutual interactions among factors. A prerequisite for such an experiment is to identify the dominant factors.

To this end, a full plan (of a full factorial experiment) can be used with experiments covering all identifiable factor combinations. For speed and efficiency, it is best to reduce the number of factors to those having the greatest impact on process outputs. Any rise in the number of factors will geometrically increase the number of possible interactions, adding to study complexity (Khavkar *et al.*, 2018; Pankaj *et al.*, 2020).

To achieve the above, one should examine the options of reducing the number of interactions considered in the study. It is recommended that the relevant action plan account for characteristic interactions among factors. Based on the relationships and values of relative interactions among the factors, one can establish the following:

- If mutual interactions among factors are weak or non-existent, the factors can be presumed to have no interactions with others. This means that the operation of one factor will not affect that of another,
- If the impact of the operation of one factor is weakened or otherwise modified by another, the factors should be deemed to interact, as are their impacts.

Based on standard deviations identified in individual experiments, it is possible to estimate the standard deviation for the entire experiment and confidence intervals for individual interactions. It is assumed that to obtain reliable results, every experiment should be repeated multiple times. If the impact of factors  $Y(X_i)$  lies within the confidence interval, the factor may be deemed not to affect process outputs significantly, and therefore may not be considered a key parameter.

The complexity of the procedure suggests the option of applying the so-called fractional plans. Fractional plans are used for multiple factors affecting the outcome of the analysis. A necessary condition for the use of a fractional plan is that the factors involved do not interact with others. This requires ensuring orthogonality while maintaining controllability.

The relevant procedure, with reference to the specific nature of occupational safety and to the creation of an environment conducive to the mitigation of hazards and untoward factors, are given in section 4.

#### **4. Guidelines for Designing a Study Procedure to Assess Occupational Safety and Mitigate Hazards and Untoward Factors**

Shainin's methodology provides a structured, duplicable, knowledge-based set of measures (Hamrol, 2005; Pankaj *et al.*, 2020). It can be seen as an aid for designing process environments and ensuring worker safety (Belavendram, 1995).

Given the identity of factors describing the working environment and factors describing object parameters as well as the option of employing quality engineering guidelines for assessment purposes, one can assume that it is possible to use quality management tools to assess the quality of the working environment (Górný, 2019).

Shainin's experiment techniques are used to identify and eliminate the root causes of defects in the working environment. Such defects may include:

- Insufficient professional training of persons tasked with performing processes and persons overseeing process performance,
- Failures to comply with expected processes parameters,
- Inadequate technical condition of machinery and equipment,
- Discrepancies between actual manufacturing processes and their specifications,
- Failures to ensure the required oversight over production contractors and the process environment,
- Failures to satisfy production standards, including adverse impacts on the environment.

The above are the most common causes of hazards and untoward factors having an adverse effect on the qualitative parameters of the working environment (Górný, 2020). Such causes require measures to prevent defects defined as deviations from required and obligatory states. In the context of working environment factors, such causes can be deemed to constitute failures to comply with requirements enshrined in relevant laws and standards.

In view of the above standards as well as the guidelines for applying Shainin's experiment design methods set out in Section 3, the algorithm below can be used to identify factors that significantly affect workers' ability to function in the working environment.

**STAGE 1:** The use of variance sheets:

- Initial state: A large number of factors describing the working environment have been identified.
- Measures taken:
  - Select the factors that significantly affect safety,
  - Assign identified situations to factors describing the working environment,

- Recognize factors describing the working environment as controllable, i.e. as factors that can be influenced for specific benefits.
- End state: A reduced number of factors describing the working environment.

**STAGE 2:** Determination of the magnitude of interactions between factors describing the working environment.

- Initial state: Limited number of factors describing the working environment are identified and recognized as controllable.

**SUBSTAGE 2A:** Analysis of controllable factors.

- Measures taken: Identify and describe controllable factors by indicating:
  - $X_{i+}$ : hazard or untoward factors that have a positive effect on safety (increase occupational safety),
  - $X_{i-}$ : hazard or untoward factors that have an adverse effect on safety (decrease occupational safety).

**SUBSTAGE 2B:** Identify input data for the main study.

- Measures taken: Identify causes of safety deterioration:
  - a) if  $q < 1.25$ :
    - Safety deteriorates as a result of normal performance of work, the variance of relationships, or
    - The decline in safety is caused by factors other than those considered in variance assessment, or
    - The causes of decline in safety cannot be clearly identified, meaning that the process needs to be modified,
  - b) if  $q \geq 1.25$ :
    - The decline in safety is caused by factors considered in the preliminary study.

Once  $q \geq 1.25$  has been achieved, one can proceed to the next stage of the procedure, which involves setting upper and lower control limits, which, if exceeded, trigger measures that bring process variance into range. An example of the foregoing is a machining process that generates noise more than permissible limits with adverse effect on worker safety, as well as the use at work of chemicals whose presence in the working environment poses hazards to workers.

**SUBSTAGE 2C:** Complete assessment.

- Measures taken:

By following the procedure, an organization identifies hazards and untoward factors that:

  - Have no effect on safety at the workstation,
  - Affect occupational safety at a workstation with sufficient severity to render the impacts of other factors (untoward factors) insignificant,

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- Although affecting workstation safety, occur alongside other hazards and untoward factors that are also of significance, making it necessary to account for synergy effects among them.
  - End status (on completion of STAGE 2):
    - The circumstances are described by highlighting key factors for workstation safety.

The procedure guides organizations to find if hazards and untoward factors affect occupational safety.

**STAGE 3:** Classic experiment.

- Initial state: The circumstances at hand are described by reference to a set of factors having the most significant impact on occupational safety.
- Measures taken: Interactions found among the factors identified at Stage 2 reveal:
  - Factors that should be deemed not to interact with other factors in their impact on occupational safety,
  - Factors that should be deemed to interact with other factors in their impact on occupational safety (each factor affects another factor in its impact).
- End state:
  - Insights are gained into the most unfavorable work-related situations that generate hazards and untoward factors,
  - Insights are gained into the objectives and scopes of necessary improvement measures.

## 5. Concluding Remarks

Occupational safety may be assessed by quality management and management aid methods. The advantage of such methods is their inherent potential to identify the causes of defects. The experiment methods developed by Shainin are designed to aid management and enable organizations to improve areas that are critical for process performance.

A key prerequisite for their use is the advanced skills required of persons conducting relevant assessments and the time delay to the achievement of desired outcomes. As an advantage, the methods help incentivize workers to engage in teamwork and significantly and lastingly improve process quality.

To make improvement measures more effective, it is vital to unambiguously identify the factors that either do not contribute to safety in a significant manner or that have no impact on the problem at hand. This substantially reduces improvement measure rollouts (by better targeting problems) and lowers the costs of such efforts (by ensuring the most efficient allocation of resources). Quality management tools provide a broad view of possible problems and enable their accurate assessment.

One should nevertheless bear in mind that desired outcomes are best achieved by employing methods that are adequate for (or dedicated to) specific issues and that best reflect their complexity.

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