

## Article

# Modeling of Causes and Consequences of Human Error in Mining Processes Design: A Qualitative Study

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**Abstract:** Given the significant role of mining in sustainable development and its intrinsic characteristics, the hazards and potential consequences are a great concern for the industry. A design error is one of the main reasons behind accidents and environmental disasters. This study aims to identify and categorize effective factors influencing design errors and their health, safety, and environmental consequences. The study was carried out based on the theme analysis of 12 Iranian surface miners' opinions from 14 October to 25 December 2021. The data were collected using semi-structured interviews. The data analysis procedure was conducted based on the Strauss Model using MAXQDA2022. In the open coding section, 120 and 146 primary codes were identified regarding causes and consequences, respectively. As for the codes for causes, 26 main categories and five subcategory codes were identified, including organizational, personal, environmental, occupational, and external factors. As for the identified codes for consequences, 11 subcategories and three main categories were identified, including safety, health, and environmental effects. The findings of the study revealed that among causes, the external factor ( $p = 0.3703$ ) had the weakest, and the personal factor ( $p = 0.003$ ) had the strongest correlations with human error in design. In line with the opinion of the expert participants, design error had significant relationships with safety ( $p = 0.002$ ), environmental ( $p = 0.01$ ), and health effects ( $p = 0.034$ ). The cause-consequence model introduced in this study can help many organizations, particularly surface mines, to provide a good basis for achieving sustainable safety, health management, and sustainable development.

**Keywords:** design for sustainability; design error; latent-content analysis; cognitive processes



**Citation:** Mohammadfam, I.; Bascompta, M.; Khajevandi, A.; Dehghani, H. Modeling of Causes and Consequences of Human Error in Mining Processes Design: A Qualitative Study. *Sustainability* **2022**, *14*, 14193. <https://doi.org/10.3390/su142114193>

Academic Editor: Rajesh Kumar Jyothi

Received: 15 August 2022

Accepted: 27 October 2022

Published: 31 October 2022

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## 1. Introduction

Design for safety and sustainability is a practical approach to address the challenges and issues associated with product design [1,2]. Designers play an essential role in achieving this goal; they should design and develop highly safe and sustainable systems with the fewest possible errors to gain satisfaction from customers and employers [3]. Despite many advances in design and stringent regulations, errors continue to occur [4,5]. Errors can directly or indirectly impact: health [6], safety [7–9], environmental [1] costs, timing, and performance [10]. For instance, the root cause of 80 to 90% of accidents that occur in the construction sector is due to design errors (DEs) [11]. DEs and rework cause complexity in the project [12]. Designers are responsible for 40% of errors on a construction project [13]. The reason Ref. [14] introduced this critical factor as the latent human error is because the consequences are not immediately known, and their identification takes longer, requiring a systematic approach.

Design errors usually occur in a product's manufacturing and operation phases, so the cost of their correction usually increases exponentially [15]. Cho defines DEs as the result of a designer's actions and decisions in product development that lead to failure [16]. Many scholars identify that human error results from failures in individuals' cognitive processes, such as detecting, understanding, and action failures [17–19]. Designing is an occupation that engages all cognitive processes of an individual [20]. Therefore, DEs mainly result from failures in cognitive processes [21]. A combination of factors known as 'performance shaping factors' affects cognitive processes and increases the chance of human error occurrence [22]. As there is no significant difference among individuals in cognitive processes, committed human errors are more influenced by background conditions and characteristics such as individual, organizational, and environmental factors [23]. Thus, selecting the best strategies for controlling human error and relevant consequences depends on detecting significant factors that can affect cognitive failures [24]. Unfortunately, research on DEs, their influential factors, and their consequences are minimal. Most of the studies conducted in the 20th century have focused on errors in the operational phase [25]. Identifying and controlling design errors and the factors affecting them is one of the most important strategies for risk control and safety improvement [26]. Mines are one of these sectors in which DEs are essential due to the vast operating space, variety of minerals, and many consequences (occupational and public health, environmental, safety, social, and economic) [27,28]. Iran is one of the countries where a large part of its economic and social development depends on mining [29], having the 7% of the mineral resources in the world [30]. Mining industries in Iran have experienced an increase in accidents in the last decade [31] and essential environmental and public health challenges [32]. Besides, no comprehensive and systematic study has been carried out to investigate factors affecting DEs and their consequences in the mining industry. The identification and categorization of design errors, together with their causes and consequences, can help design teams prevent such errors and manage the situation more efficiently. Consequently, this study aims to explore, categorize, and determine the relationship between factors affecting human error in design and the relevant safety, health, and environmental consequences in surface mines from Iran, introducing a qualitative model based on expert opinions.

Further, the study contributes to the literature in several ways:

- There is a lack of qualitative studies/articles exploring the effectiveness factors of design errors, especially in mines. Therefore, this study is believed to fill a gap in the existing literature.
- The study provides essential theoretical outcomes and suggestions, especially for researchers.
- Our results offer some practical implications for managers and safety experts in the mine design process error management.

## 2. Review of Previous Research

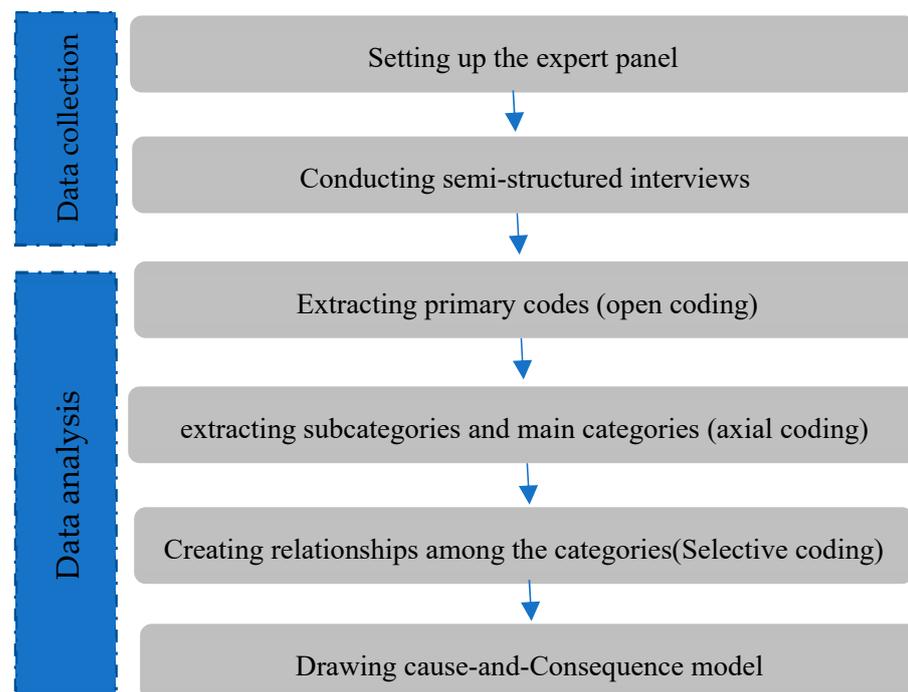
Based on previous studies, several factors affect design errors. The study by Wang et al. on factors of DEs in Construction Projects showed that the five factors of human, method, material, machine, and environment are the root causes of DEs. The findings of their study showed that sustainable development could be guaranteed by identifying and controlling factors affecting Des [33]. The results of the study by Yuan et al. [34] revealed that the experience and knowledge of designers are effective factors in reducing design errors and safety risks. Hernan [35] reported that Standardization of design procedures and processes, encouraging collaboration and information sharing, the support of the top management of the organization, and designer expertise might help reduce DEs and promote health and safety during construction. Knotten et al. [36] noted that poor management during the design phase is one of the factors influencing the DEs. Herrera et al. [37] stated that poor communication and coordination among project teams during the design phase lead to DEs and Poor design performance. Inadequate knowledge of designers in the field of safety and their low participation in the implementation of the safety management

system is one of the main factors in the occurrence of errors and the reduction of the safety level of products and equipment [38]. Ajayi and Oyedele [39] reported that a lack of understanding of the project requirements by designers might cause DEs. The results of the study by Wimalasiri et al. [40] showed that lack of knowledge, poor training procedures, poor selection procedures, work pressure, lack of first-hand experience of constructions, lack of cooperation between stakeholders, Conflicts of interest between stakeholders and disciplines, management and designer attitudes to safety, and industrial influences have a significant influence on DEs in the UK oil and gas industry. The results of the study by Yap et al. [41] revealed that the design review was the most influential factor in identifying design deficiencies and errors. Surlan et al. [42] stated that the decisions made during the earlier stages of the design process are very effective in controlling design errors and the success of the project. DEs are a fundamental challenge for many industries that need to be identified and managed [43,44].

The remaining of this paper is arranged as follows. Section 2 explains the methodology and data collection procedures. Section 3 presents results, analysis, and findings and discusses managerial implications. Section 4 concludes the research, highlighting limitations and directions for future research.

### 3. Materials and Methods

This study is a qualitative investigation using data-based strategy and latent-content analysis to identify and categorize influential factors and their consequences regarding surface-issue design errors. The roadmap and steps for conducting the study are presented in Figure 1.



**Figure 1.** Roadmap and steps of conducting the study.

#### 1. STEP1: Setting up the expert panel

In a qualitative Study, the expert panel should consist of experts with full command over the topic. Therefore, the expert panel in our study went through a rigorous selection process. After reviewing several experts' experiences in the mine design field, a group of 12 experts was selected via the non-probability sampling method based on four characteristics: knowledge, experience, inclination to participate, and time adequacy. The literature

shows that theoretical saturation has also been identified as the most common sample size method in qualitative research [45,46].

## 2. STEP2: Conducting semi-structured interviews

Semi-structured interviews were used to collect the data. The study participants were allowed to leave the interview sessions whenever they wished to glean more reliable data. All the participants completed consent forms and were assured that their names remained confidential and were only used for research purposes [47]. The interviews were conducted in the Persian language. The duration of the interviews ranged from 45 min to one hour. Each interview was immediately analyzed after it was done, and the acquired feedback was used for the subsequent interviews. The interview sessions continued till the contents were saturated. The saturation point was reached after 12 interviews in this study.

## 3. STEP3: Extracting primary codes (open coding)

After transcribing the interviews into texts, the extraction of information was carried out based on the systematic Strauss-Corbin model, including open, axial, and selective coding procedures [48]. First, the primary codes of concept units were extracted using the MAXQDA software version 2022 [49,50].

## 4. STEP4: Extracting subcategories and main categories (axial coding)

Axial coding is the second level of the coding process [51]. In this step, the codes conceptually related to each other were clustered as categories. In the axial coding step, the identified categories were clustered, and core categories were determined [52]. The categories finalized from axial coding serve as the axis point or hub in axial coding. This coding stage aims to create a framework that details the specific conditions that give rise to a phenomenon's occurrence.

## 5. STEP5: Creating relationships among the main categories (Selective coding)

The final qualitative study data analysis stage is selective coding [48]; it enables the researcher to select and integrate categories of organized data from axial coding in cohesive and meaning-filled expressions [53,54]. Eventually, the researchers identified the relevant hypotheses using the scale coding tools in MAXQDA22, having a long-time engagement with the quantitative and qualitative literature and using expert opinions in a focus group; they reached a final model in the selective coding step.

## 4. Results and Discussion

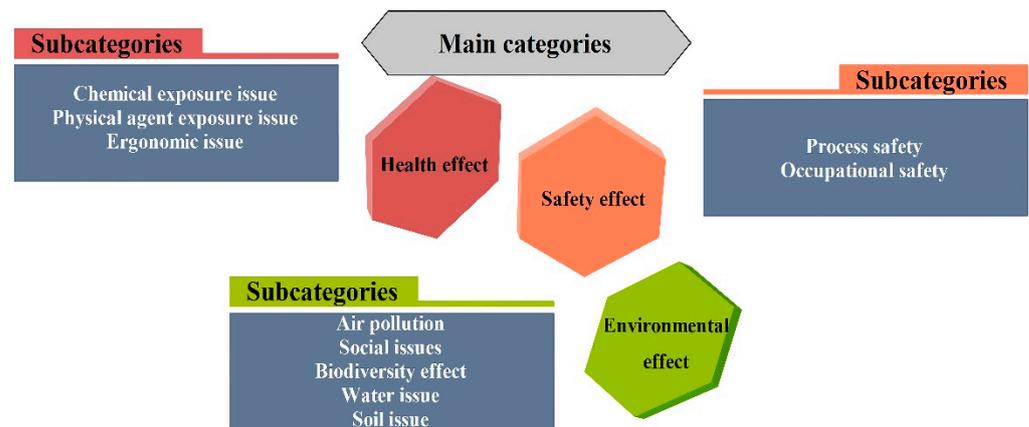
The current study included 12 Iranian surface mine design experts. Table 1 displays the demographic information of the participants.

**Table 1.** Demographic variables of the experts.

Demographic Variables	Total	Percentage
Gender		
Male	9	75.00%
Female	3	25.00%
Educational		
Bachler	1	0.08%
Master	6	50.00%
Doctoral	5	42.00%
Experience in mine design		
5–15 years	7	58.33%
>15 years	5	41.67%







**Figure 5.** Main categories and subcategories of Consequences of human error in mine design.

#### 4.3.1. Factors Affecting Human Error in Surface Mines Design

##### A. Organizational Factors

The subcategories include poor management, safety design culture, and resource allocation.

- Poor Management

Management is one of the most critical aspects of organizational factors, which can heavily influence design errors [56]. Participant No. 10 mentioned, “I used to work as a designer in big surface mining in Iran. The human resource manager was very self-conceited and secretive. He rarely listened to the experts’ opinions. Most of the staff were scared of him”. Some studies investigated the responsibilities of the management team in the occurrence of human errors and reported that lack of appropriate interactions between organizational management and the employees is one of the leading causes of human error, hence suggesting that instead of finding someone to blame, organizations should better try to find practical strategies to identify and deal with such challenges in their organizations [57].

- Safety Design Culture

Safety design culture is a must for organizations with a design office because it is essential for identifying potential human error in design [58]. “Unfortunately, the safety culture in Iranian mines is very poor. Designers naturally try to create safe designs with the fewest possible errors. However, it is not enough as all the staff, particularly the managers, should ensure safety and try to provide suitable conditions for a safe design” (Participant No. 12). Safety design culture, designing for safety. The managers’ obligations are all root causes of having safe products and processes [59].

##### B. Individual Factors

- Poor Resource Allocation

Providing a proper resource allocation is one of the primary responsibilities of organizations, which is called resource management. Participant No. 7 mentioned, “Like any other job, designing needs the proper allocation of resources, including hardware and software equipment so that the designer can create the safest and most exact designs”. This aspect can affect the timing of projects and their safety levels. To carry out worthwhile projects with the fewest errors, project managers need to analyze the required resources carefully and provide proper resources. This factor includes technical knowledge, experience, interest, job satisfaction, fatigue, sleep disturbance, risk understanding, training level, health condition, gender, and personality type.

- Technical Knowledge, Experience, and Interest

Technical knowledge, experience, and interest were the three personal factors in axial codes that participants argued affected the occurrence of human error in design. For

example, participant No. 8 said, “I am a mine designer, not an airplane designer, you know why? Because I do not have the necessary knowledge to design airplanes. I think the starting point in every job is to have the required knowledge; otherwise, one cannot be successful at all. Experience in my design will not increase with age. I know some people who call themselves designers after doing minor designing jobs. We cannot call them experienced designers. On the contrary, some designers who, despite being young, have conducted large-scale, important projects; they can be called experienced designers”. Technical knowledge and experience are labeled as performance shaping factors (PSF) in human error research, resulting in severe consequences if not observed [60–62].

- Job Satisfaction

Job satisfaction is essential in maintaining human resources in organizations [63]. Job satisfaction can affect individuals’ motivation and, thus, increase or decrease their performance level while working, paving the way for committing human errors [64]. For instance, as one of the main components of job satisfaction, poor financial satisfaction can deteriorate motivation levels in designers’ design planning and processing [65]. For example, participant No. 8 stated, “As a designer, I should be able to work independently, feel safe at work, and feel satisfied regarding my payment and perks”.

- Fatigue and Sleep Disturbance

Fatigue and sleep disturbance are the most significant factors causing human error. Participant No. 5 mentioned, “Sometimes, I feel I have no energy left and cannot do anything. I feel that I have lost my focus, and I feel so exhausted that I feel like sleeping right there”. From a cognitive point of view, fatigue can significantly reduce information processing abilities and thus increase reaction time and carelessness and decrease awareness and focus, resulting in more occupational accidents [66,67]. Research shows that adverse sleep quality changes can bring about detrimental psychological consequences such as attention loss, understanding difficulties, and learning/memory disorders [68].

- Risk Perception

Risk perception is one of the essential design factors emphasized by many designers. Participant No. 3 stated, “Accidents in the mining industry can be very severe, so many designers carefully reflect on potential hazards while designing”.

- Training Level

Another critical factor in controlling errors is the training level of designers. For example, participant No. 6 said, “A designer should be required to update himself with new designing methods, organizational and environmental changes, and many other factors. Sufficient, updated training is one of the best tools to make sure that designers are updated enough”. Training can increase designers’ situational awareness and result in the reduction of errors [23].

- Health Status

“Designing is a sensitive and precise job. “A designer should be physically and mentally healthy” (participant No. 1). Physical diseases and mental disorders are two critical factors affecting performance.

- Personality Type and Gender

Participant No. 11 believed that personality factors affect human error in design by stating, “I think sharp focus and rapt attention significantly influence designing performance. These two features are more prominent in introverted individuals”. Some researchers believe that errors have internal causes related to cognitive mechanisms. One of the most critical internal causes is individuals’ personality issues, including mental disorders and emotional instability (introversion, extroversion, flexibility, agreeableness, and consciousness).

Female participants emphasized the role of gender in errors and believed that female designers could show more precision in my designing process. “They are more meticulous and pay more attention to small details” (participant No. 5). Saptari et al. showed that women commit fewer errors in activities needing assiduous attention [69].

#### C. External Factors

The identified external factors included pressure from legal organizations, work-family conflict, the pressure of competitors, and sanctions.

##### The pressure on Legal Organizations

Many participants emphasized the negative role of non-professional legal requirements and constant changes in the process of mine designing in Iran. Participant No. 1 said that “We live in a country where rules and regulations are constantly changing. Such changes put firm pressure on employers, making them force designers to come up with their designs faster than usual”.

##### Work-family Conflict

Work-family conflict is one of the main external factors that can affect the designer’s occupational performance. Participant No. 2 pointed out, “Sometimes, I am involved with a project so much that my family complains about it. I always think about what they say about my job”. Obrenovic showed that family could harm people’s psychological well-being and safety and thus increase the chance of an error [70].

##### Pressure of Competitors

“Every year, many mining engineers graduate from Iranian universities and become ready to enter the job market. Recent graduates are more familiar with updated information and technology than previous ones; they are trying to prove their efficiency to the market but lack enough experience. The mining industry has a huge gap between theory and practice”. High salary demands by experienced designers and low salary demands by inexperienced designers pave the way for employers to hire inexperienced designers for essential projects, leading to more human error in design [65].

##### Sanction

One of the most severe challenges for Iranian mine designers is sanctions; these sanctions include the lack of access to updated recourses, equipment, and technologies and well-known experts in the field. Participant No. 7 mentioned, “We use highly-advanced sophisticated software for designing, but unfortunately, many features of these software pieces are locked, and we cannot buy them due to sanction. We also face many problems regarding buying hardware and technological equipment and having access to mine designing figures worldwide”.

#### D. Environmental Factors

The focus and performance of human beings are influenced by environmental conditions and personal features [71]. Workplace noise, poor lighting, and thermal comfort are important factors affecting design error.

##### ■ Noise

Noise is a stressor at work that can upset the physiological balance of individuals and increase the chance of human error [72]. Working memory is one of the essential tools for performing one’s duties appropriately and preventing human errors in sensitive jobs [73]. Participant No. 6 stated, “One of my colleagues who is very knowledgeable and experienced in mine designing loses his focus with the slightest noise distraction possible. Generally, for precise works like designing, the environment should be quiet”.

##### ■ Poor Lighting

Another stressor is the poor lighting at the workplace. All the negative impacts of poor lighting are in effect through the eyes [74]. Participant No. 3 said, “I try to draw

the curtains away and use daylight at my workplace. I usually change my computer monitor because the image of the window or bulbs reflects on the screen". Research shows that the intensity and temperature of lighting can bring about psychological consequences and reduce cognitive performance [75,76]. The type of lighting source can be an influential factor influencing the performance and recovery of the staff [77].

#### ■ Thermal Comfort

Hotness and coldness are the two thermal comfort variables. "Most surface mines in Iran are located in extremely cold or scorching locations; these variables can negatively affect thermal comfort and make the condition ripe for human error" (participant No. 12). Facing thermal stress increases reaction time, causes lapses in short-term and long-term memory, decreases understanding, and deteriorates the computational performance of the individuals [78,79].

#### ■ Indoor Air Quality

Exposure to chemical contaminants, air particles in the workplace, and the high intensity of carbon dioxide can detrimentally affect designers' cognitive performance [80]. Participant No. 9 said, "When I get to my workplace, I have to open up the windows to change the air unless it is so cold or hot outside. If I do not change the air, I have a sore throat, red eyes, boredom, and fatigue".

### E. Task Factors

The job complexity and novelty, design process type, and long-term/short-term designs are effective factors influencing human error in design.

#### ➤ Complexity and Novelty

The majority of participants believed that mine designing is a highly complex job. "In mine designing, there are lots of uncertainties. The most insignificant error can result in devastating consequences for the equipment, workers, and even the population living around a project" (participant No. 5). Complexity and novelty raise the mental load of the designer and increase the chance of human error [81].

#### ➤ Design Process Type

Many designing processes in the mining industry are repetitive and thus reduce the chance of errors, especially compared to other processes with a lower frequency of occurrence. "Designing explosions for mining projects is a repetitive process. Designers reach a fixed and safe method gradually. So, designing such processes needs a higher level of trust" (participant No. 11).

#### ➤ Long-term/Short-term Designs

Surface mining excavations have a hierarchical design plan including day-by-day (short-term) functional designs such as truck dispatch, the positioning of the equipment, and control of crusher feed characteristics and long-term operational designs such as the introduction or building of new infrastructure and the opening or closing of regions of the mine site [82,83]. participant No. 7 pointed out that "Long-term designing is usually more susceptible to human error in design than short-term designing because there is no sufficient information available to the designer".

### 4.3.2. Consequences of Human Error in Surface Mine Designs

The negative consequences of design error can not only exert effects in the mining area but also cause hazards and risks for the environment and the regions around the mining area. The main categories of consequences include safety, health, and environmental categories.

#### A. Safety Effects

The identified subcategories of safety include process and occupational safety.

##### ✓ Process Safety

The safe design of mine processes consists of designing access roads, work steps, explosions processes, excavation, and other mining sectors. Research demonstrates

that insufficient safety is the leading cause of more than 60% of accidents [84]. “I remember once a designer had miscalculated the sloping degree of an access road more than he should have; in addition to severe financial losses, the road made drivers extremely tired and increased the chance of accidents” (participant No. 21). The wrong design of the slope of steps in the mines not only increases the costs of later modifications but also raises the possibility of accidents [85]. Participant No. 11 mentioned, “The designing of explosions in the mines can be very dangerous because it is repeated repeatedly. Rock fly is one of the most significant dangers in this regard, which is the second cause of death among workers after mine collapse in Iran”. Together with earthquakes and dust fallout, rock fly is one of the dangerous consequences of explosions in mines that can cause serious accidents. Human error in design can make these consequences more serious [86].

#### ✓ Occupational Safety

The subcategories of this section include errors in the design and installment of machines, electrical equipment, pressure systems, and fire systems. The appropriate equipment design can directly affect mine workers’ safety [87]. “Because most of the installed equipment runs on three-phase electric power, the inappropriate design of earthing systems can cause the electrocution of mine workers” (participant No. 12). “A designer can face some limitations while designing such as financial resources, knowledge recourses, and experiential resources making him make errors in the process of designing and endanger the lives of workers” (participant No. 7). Considering the human-system approach in design has been suggested to deal with the challenges of the effects of design error on safety and personal health [88].

#### B. Health Effects

The participants from the two viewpoints emphasized the health consequences of human error: the effects of design error on mine workers and the effects of design error on the people living around the mining area.

##### ○ Chemical Agent Exposure Issue

Workers’ exposure to steam, gasses, and dust is one of the leading causes of occupational diseases like silicosis. “We cannot say that it is the designer’s fault to produce dust in the mining area because dust and other air pollutants are an indispensable part of mining. Nevertheless, design errors can deteriorate the situation. For example, errors in designing explosions or choosing appropriate excavation machines can expose workers to poisonous compounds and dust” (participant No. 6).

##### ○ Physical Agent Exposure Issue

Noise, vibration, and inappropriate lighting are the most critical physical subcategories emphasized by the participants. “Mining activities are always noisy. Committing errors in designing the appropriate selection of equipment and mining processes can expose workers to extra noise or even severe vibration; these issues can also affect the lives of people around the mining area as they always complain about the explosions and relevant noises of the mines” (participant No. 5). Participant No. 1 stated that “the death of ship around the mining area was significantly high. After conducting some research, it was found that due to continuous explosions, the ship was shocked and had heart attacks. Finally, it was reported that the designer’s design of explosion patterns was unsuitable and caused such consequences”.

##### ○ Ergonomic Issue

It can be claimed that the root cause of many ergonomic issues in mine workers, such as musculoskeletal disorders, mental problems, financial and occupational dissatisfaction, occupational stress, and high working load, is poor design [89]. Participant No. 6 said, “Design error in the estimation of minerals in the mines (more or less than it is) can affect the planning procedures of mining units. If more than the actual amount is

estimated, it can cause financial costs and layoffs. If less is estimated, it can severely increase the workers' working load and physical/mental issues".

#### C. Environment Effects

The environmental consequences include the subcategories of water issues, air issues, soil issues, economic effects, social effects, and biodiversity.

##### ❖ Water Issue

The contamination of underground and fresh water, lack of sufficient access to water, and the destruction of quants and springs are all consequences of mining activities. Design error is one of the main reasons for water contamination. "For example, designer error in choosing the appropriate gold extraction process in a mine can contaminate the water of villages in the mining area. People have used this water for a long time. The high incidence rate of cancer in the area suggested the villagers' exposure to arsenic elements. Water contamination was reported to be the cause of this accident" (participant No. 8). The acidic wastewater of mines is one of the worst problems arising from mining activities which has detrimental effects on surface and underground waters [90]. The main reason behind such environmental disasters is ignoring environmental issues regarding the final design of the maximum depth of the pit and planning by the designer [91].

##### ❖ Air Issue

Participant No. 6 said that "Produced contaminations resulting from human error in design can affect both mine workers and people living around the mining area with the important difference that workers usually wear protective clothing while ordinary people do not wear any protective clothing and are more susceptible to such hazards, especially women and children".

##### ❖ Soil Issue

Mining activities are always considered the leading cause of soil contamination and corrosion. "Design error can make mines unprofitable, leading to layoffs by the employers. When mines run on fewer workers, a higher workload is on the workers. Some workers rely on drugs to tolerate such a heavy workload which can then be spread to the ordinary people living around the mines" (participant No. 10).

##### ❖ Biodiversity Effect

Mining activities can also influence the environmental diversity of the region around the mining area. The direct exposure of animals, plants, and microorganisms—particularly sensitive ones—to poisonous extracted materials and water can poison them [92]. "Mining activities naturally destroy the natural habitat of many animals and plants, which a design error could worsen. A design error in estimating the exact amount of extracted materials can increase the amount of waste material around the mines contaminating the underground water" (participant No. 6). "Increased noise around the mining area due to inappropriate extraction equipment can also make lots of species emigrate from the area to other areas" (participant No. 2).

#### 4.4. Selective Coding

In this phase, the researchers selected each main category and connected it to another main category in a systematic way to prove the existence of the relationship. Graphs were used to draw the relationships between the main categories [93]. The researchers used the following tools and means to identify the relationships:

- MAXQDA scale coding tool [49].
- Long engagement of the researcher with the relevant qualitative and quantitative literature.
- Consulting with the expert panel in the form of a focus group.

Scale coding tool: In this method, participants were required to state their opinions qualitatively (scores ranging from 0 to 10) about the relationship between the causes of

failure in cognitive performance, design error, and the effect of errors on the identified consequences. Then, statistical analyses were run on the scores to prove the existence of relationships (Table 2). The results of the scale coding of causes revealed that there are significant relationships between personal factors and cognitive performance (probability rate = 99%) and between environmental, organizational, and occupational factors and cognitive performance (probability rate = 95%). However, no significant relationship was found between external factors and cognitive performance. Moreover, the hypotheses of the effects of design error on safety issues (probability rate = 99%) and health/environmental issues (probability rate = 95%) were approved. In the next step, a focus group comprising five experts with distinguished research histories about safety and ergonomics was set up to investigate the relationships between extracted factors on DEs.

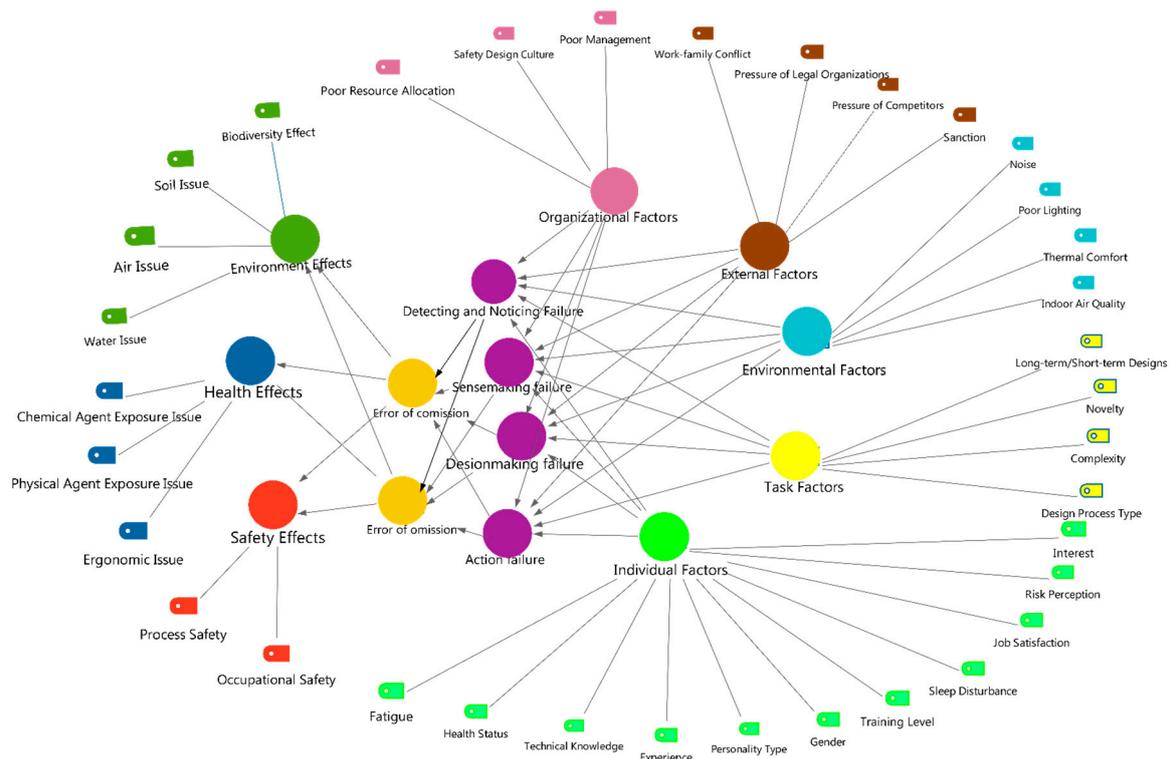
**Table 2.** Correlations between causes/consequences and design error.

	Main Categories	Correlations(R)	p-Value
Causes	Individual factors	0.923 (N = 12)	( <i>p</i> = 0.003)
	Environmental factors	0.767 (N = 12)	( <i>p</i> = 0.44)
	External factors	0.403 (N = 12)	( <i>p</i> = 0.3703)
	Task factors	0.814 (N = 12)	( <i>p</i> = 0.012)
	Organizational factors	0.565 (N = 12)	( <i>p</i> = 0.012)
Consequences	Safety effects	0.910 (N = 12)	( <i>p</i> = 0.002)
	Health effects	0.758 (N = 12)	( <i>p</i> = 0.024)
	Environmental effects	0.827 (N = 12)	( <i>p</i> = 0.01)

Figure 6 demonstrates the cause-consequence structural model of human error in surface-mine design. The findings show that personal and occupational factors are the most vital, and external and organizational factors have the weakest correlations with design errors. Despite being different in terms of the method and purpose of the study, previous studies have also emphasized the significant role of organizational and external factors in causing human error [94,95]. The results of this study show that these two factors cannot influence human error directly. However, they can directly affect individuals' cognitive performance as personal factors, and a failure in cognitive performance leads to human error. Therefore, personal factors are the most potent causes of human error compared to all other factors [96]. Personal factors are influenced by two factors: the internal tendency of an individual to display particular behavior and the favorable conditions to display such behavior. An individual's internal tendencies belong to their natural characteristics formed based on their physical, physiological, and cognitive features. On the other hand, there are some external factors that can cause particular behavior, such as experience, education and training, and fatigue [97]. The findings of this study reveal that occupational factors have the strongest correlations with failure in cognitive performance and design error after personal factors. The most important reasons may be the complexity of the responsibilities of people in social and technical systems and the demanding cognitive needs of many jobs [98].

Designing is a job that is highly demanding in terms of cognitive processes as it preoccupies individuals' cognitive systems [20]. The results of interviews with the experts in this study show that a mine designer should prepare adequately for emergencies and complex conditions in their design. Considering both routine and critical conditions in designs significantly increases the mental load, which can enhance the chance of committing more errors [99]. Moreover, the analysis of scale codes shows that most of the participants and experts in the focal group underlined the effect of environmental factors (e.g., noise, poor lighting, and air condition) on the designers' cognitive performance. Previous research has also emphasized the role of environmental factors in deteriorating individuals' cognitive performance [100,101] and creativity [102], calling them environmental distractions. The chief reason is that the human brain is extremely limited in paying simultaneous attention to different issues. Thus when it happens, the quality of the performance targeting the

main task decreases significantly [103]. It is obvious that failure in cognitive performance is the link between performance-shaping factors and human error [22]. Given the similarities of the mechanisms of cognitive performance among individuals [104], it is necessary to prevent the consequences of human error in design by identifying and removing cause factors [105]. The essential consequences of design error can include safety, health, environmental, and economic effects. Adams et al. categorized these consequences and presented them as a risk-assessment matrix [106]. The effect of design errors on safety and health is entirely tangible in a way that removing or reducing design errors can directly improve the safety and health levels of an organization [107]. Thompson argues that removing or reducing road accidents in mining areas depends on human-factor interactive effects and designing features such as geometric, structural, and functional design components [108]. The results of the analysis of interviews in this study are in agreement with previous studies regarding the direct and indirect effects of design error on environmental consequences. The most important environmental consequences introduced in mining studies include soil, water, and air contamination, the destruction of natural vegetation, and negative effects on the studied areas' economic, social, and cultural conditions [109]. Of note, most previous studies have focused on the consequences of mining activities and operational sectors [32,90], ignoring the role of designers altogether. It should be mentioned, however, that it is the case for many fields of studies, as Salvendy maintains that most studies conducted in the 20th century have almost focused on errors committed by workers and end-users [25].



**Figure 6.** Research conceptual model.

Qualitative research is one of the most effective and cost-saving tools [93] for the realistic identification of causes and consequences in complex behavioral, emotional, organizational, and social areas of investigation [110]. Therefore, this study can provide informative answers via a qualitative model to the following questions with introduced hypotheses to be tested in future quantitative studies: What factors cause a human error in design? What are the consequences of human error in design?

Like other studies, the present study also has some limitations that should be considered in future research. The sample size is small, being a common feature of qualitative

research. However, it was inferred that conducting the study with several experts would increase the reliability and impartiality of the process. Besides, this study is focused on surface mines, with their particular organizational culture and missions. Hence, care must be taken to generalize the findings to other types of mines or industrial sectors. This study investigated the environmental, safety and health consequences of DEs. Future studies could investigate other consequences of DEs, such as cost and rework. Finally, to investigate the relationships between the identified factors, it is suggested that future studies use Multi-Criteria Decision-Making (MCDM) methods like TOPSIS, AHP, ANP, ISM, etc.

## 5. Conclusions

Design error, also labeled latent human error, is a critical factor behind many occupational accidents. This study has identified the causes and consequences of human error in design based on a data-driven theoretical strategy and thematic analysis. Regarding the causes of human error in design, four hypotheses were formulated out of five extracted concepts based on the axial coding of causes. Focal sessions were held with the experts; eventually, all five concepts were approved by the experts. As for the consequences of human error in design, three hypotheses were approved based on the scaled coding and the experts' opinions in the focus group.

The present study also has numerous implications for mine managers, government planners, and safety experts. From a managerial perspective, a good understanding of the root cause of design errors enables managers to direct their efforts toward improving the inherent safety level of the mine. Furthermore, this study can guide government planners to understand the nature of incidents and formulate strategic policies to implement and monitor health, safety, and environmental rules in surface mines. The findings will assist safety experts in providing more effective hazard identification, risk assessment and determining controls, establishing objectives and programme(s), identifying training needs associated with its HSE risks, operational control, emergency preparedness and response, incident investigation, nonconformity, corrective and preventive action, and audits programme.

**Author Contributions:** Data curation, A.K. and H.D.; Formal analysis, I.M. and A.K.; Funding acquisition, H.D.; Investigation, A.K.; Methodology, M.B., A.K. and H.D.; Writing—original draft, M.B.; Writing—review & editing, I.M. and M.B. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by the Hamedan University of Medical Sciences and Health Services and grant number 140008257113.

**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki, and approved by the Institutional Review Board (or Ethics Committee) of the national committee for ethics in medical research (protocol code IR.UMSHA.REC.1400.617 and date of approval 31 October 2021)".

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** Not applicable.

**Conflicts of Interest:** The authors declare no conflict of interest.

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