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Review

Analysis of Cognitive Biases in Construction Health and Safety in New Zealand

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Abstract: The construction industry's complexity and high-risk nature present significant decision-making challenges, often resulting in errors that jeopardise health and safety performance. Cognitive biases can further distort risk assessments and influence decision-making, ultimately affecting safety behaviours and outcomes. Although numerous studies have explored cognitive biases in construction, there remains a lack of a comprehensive understanding regarding how these biases interact with key decision factors related to health and safety. This study aimed to advance sustainable health and safety practices within the construction industry by examining the consequences and interplay of cognitive biases and essential decision factors through a systematic literature review. Two hundred and eighty-three articles published between 2018 and 2024 were analysed, with forty-five selected for inclusion. The network analysis findings identify key decision factors, reinforcing loops, and critical paths that affect health and safety performance, illustrating how cognitive biases influence risk perception, decision complexity, and workplace safety behaviours. The insights gained from this study highlight the challenges and the potential for improvement. They serve as a foundation for researchers, construction safety professionals, and policymakers to develop targeted interventions that mitigate cognitive biases, enhance risk perception, and strengthen decision-making frameworks, ultimately improving health and safety performance in the construction sector.

Keywords: cognitive biases; decision-making; construction safety; health and safety performance

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1. Introduction

Health and safety (H&S) in the construction industry is a critical concern due to the high-risk nature of construction activities [1,2]. With consistently high rates of accidents and injuries compared to other sectors, such as agriculture and manufacturing [3–6], effective decision-making is essential to mitigating workplace hazards and identifying the best action for safety management on construction sites [7]. Poor decisions, whether due to time pressure, incomplete information, unsafe behaviours, or inadequate risk assessment, can significantly compromise H&S performance, leading to incidents that may result in injuries or fatalities [8,9]. A significant factor contributing to human mistakes that result in severe injuries in construction settings is the inability to recognise hazards due to inattentiveness or lapses in cognitive function [10,11]. These lapses, often worsened by cognitive biases—systematic patterns of deviation from rational judgement—can distort decision-making processes and further compromise safety outcomes.

These biases are particularly concerning in complex systems, such as construction, where heightened uncertainties and errors in judgement can trigger unforeseen consequences and systemic breakdowns that undermine safety [12]. Cognitive biases such as overconfidence often lead individuals to overestimate their abilities, resulting in inadequate preparation or them ignoring potential risks [12]. Additionally, risk compensation can exacerbate these challenges, as individuals may over-rely on safety technologies, maintaining their perception of safety while undertaking more significant risks to adapt to increased time pressure or cognitive demands [9].

Many studies have examined how cognitive biases could affect decision-making processes. For example, research on managers in the Portuguese port sector demonstrated that overconfidence and optimism bias led to systematic judgement errors, similar to those observed in the Brazilian construction industry, where anchors significantly influenced decision-making processes [13]. Another study by Nelius et al. [14] demonstrated that confirmation bias can result in the investigation of incorrect causes of problems, which could potentially cause ineffective decision-making. Furthermore, analysis based on the theory of planned behaviour revealed that two types of optimism bias significantly influence construction workers' intentionally unsafe behaviours [15]. Positive event optimism bias, characterised by overconfidence, correlates with higher self-esteem, while negative event optimism bias, reflecting the underestimation of risks, is negatively correlated with risk preference [15]. However, the authors did not identify the cognitive biases that affect decision-making in H&S specifically. Despite these contributions, there remains a lack of a comprehensive understanding of how cognitive biases influence key decision factors in construction H&S. Addressing this gap is essential for designing effective interventions and improving safety outcomes in the construction industry.

Given the challenges posed by cognitive biases in decision-making and their impact on H&S performance, this research sought to answer the following questions:

- What are the key decision factors influencing H&S in the construction industry?
- What cognitive biases influence the decision factors affecting H&S in the construction industry?
- Which loops and critical paths involving cognitive biases influence the decision factors affecting H&S in the construction industry?

2. Literature Review

Numerous variables influence H&S performance, directly impacting worker safety and the overall project outcomes. Decision-making plays a central role in navigating the dynamic and complex nature of construction projects [16,17], where workflows are continuously changing [18] and site conditions are unpredictable [19,20]. Effective decision-making ensures that hazards are promptly identified, risks are accurately assessed, and safety measures are efficiently implemented, mitigating the potential for accidents.

Decision-making in H&S is mainly influenced by risk perception, which plays a pivotal role in identifying and prioritising hazards. According to Gernand [21], misjudging a risk's likelihood can lead to ineffective resource allocation to mitigate that risk, resulting in unpreparedness for actual incidents and ultimately heightening the overall risk exposure. Similarly, uncertainty emerges from the dynamic nature of construction projects, making it difficult to predict and manage potential hazards [22]. This uncertainty is further compounded by unforeseen site conditions, such as unexpected soil instability or sudden weather changes, which can complicate hazard management and disrupt established safety protocols [23,24]. These factors are often worsened by cognitive biases such as confirmation bias or overconfidence bias [12]. Overconfidence bias may lead decision-makers to underestimate the unpredictability of conditions or overrate their capacity to control outcomes, resulting in insufficient preparatory measures [25].

On the other hand, confirmation bias is the tendency to prioritise and understand information in a way that reinforces existing beliefs [14]. This bias may lead individuals to favour information that aligns with their beliefs, potentially overlooking critical data that challenge their assumptions. Bellamy et al. [12] stated that increasing the availability and quality of information, anticipating potential scenarios, monitoring signals, and evaluating diverse options could significantly enhance decision-making outcomes. However, if confirmation bias distorts the interpretation of such information, it can hinder effective decision-making and contribute to unsafe behaviours, as individuals may overlook safety-critical warnings or misjudge risks, further heightening the likelihood of accidents and injuries [8].

Unsafe behaviours refer to actions that deviate from established safety protocols, leading to an increased risk of accidents and injuries. Cognitive biases, such as risk compensation, could potentially influence this deviation. Risk compensation occurs when individuals adjust their behaviour in response to perceived safety measures, potentially increasing unsafe behaviours when workers feel overly protected [25]. Additionally, time pressure and productivity demands play a significant role in shaping risk compensation. Overestimating the benefits of safety measures, underestimating the risks of a situation, and focusing narrowly on achieving goals can lead workers to discount the dangers of risky actions, resulting in an over-reliance on safety interventions [9,26]. These factors are deeply interconnected, influencing decision-making processes and the overall H&S performance in construction environments.

This study aims to contribute to the construction safety literature by equipping professionals and academics with the necessary knowledge to identify and address the factors and cognitive biases that influence decision-making in H&S. By understanding these factors and their interactions, there is significant potential for enhancing safety practices, resolving issues early, and reducing the likelihood of accidents.

3. Research Methodology

The dynamic and evolving nature of the construction industry requires continuous adaptation and innovation to tackle challenges effectively. Although there has been considerable research on general safety practices, the specific influence of cognitive biases and decision-making factors in H&S performance remains relatively underexamined. A systematic literature review (SLR) was conducted to explore this topic systematically. A SLR is a critical method for evaluating previous research by identifying, selecting, and assessing studies that address specific research questions [27]. This research used 3 databases, Scopus, ScienceDirect, and EBSCO, capturing a broad range of high-quality papers related to the research objectives to ensure the comprehensive coverage of the scope and domain.

3.1. Database Search

Firstly, a structured search strategy was developed to identify the literature relevant to the research topic. The keywords for the literature search were divided into three groups: the first group focused on cognitive biases, the second group targeted decision-making and H&S performance, and the third group was related to the construction industry. This grouping approach was employed to ensure a balanced inclusion of studies covering cognitive biases, decision-making, and their specific applications in construction safety.

The initial set of keywords was taken from the research objectives for each group. Synonyms and related terms were then sought and added to the search strings to ensure inclusivity and capture a broader range of relevant studies. Additionally, VOS Viewer was used to refine the selection of keywords based on the most recent search results. VOS Viewer was employed to analyse keyword co-occurrence and identify emerging themes from the existing literature [28]. This method ensured that the search strings captured recent publications' most relevant and current terminology.

The final search string used on Scopus after combining these three groups was as follows: (TITLE-ABS-KEY ((cognitive OR mental OR behavioural OR behavioral) AND (bias*)) AND TITLE-ABS-KEY ("safety management" OR "health and safety" OR "risk assessment" OR "risk perception" OR "risk management" OR "decision-making" OR "decision making" OR "occupational risks" OR "wellbeing" OR "well-being" OR "accident prevention") AND TITLE-ABS-KEY (construction OR engineering)). Similarly, the strings were adjusted for ScienceDirect and EBSCO to suit their search features and are detailed in Table 1.

Table 1. Search keywords for literature search.

Database	Search Strings
Scopus	(TITLE-ABS-KEY ((cognitive OR mental OR behavioural OR behavioral) AND (bias*)) AND TITLE-ABS-KEY ("safety management" OR "health and safety" OR "risk assessment" OR "risk perception" OR "risk management" OR "decision-making" OR "decision making" OR "occupational risks" OR "wellbeing" OR "well-being" OR "accident prevention") AND TITLE-ABS-KEY (construction OR engineering))
ScienceDirect	(construction OR engineering) AND ((cognitive OR mental OR behavioural OR behavioral) AND (bias OR biases)) AND ("safety management" OR "health and safety" OR "risk assessment" OR "risk perception" OR "risk management" OR "decision-making" OR "decision making" OR "occupational risks" OR "wellbeing" OR "well-being" OR "accident prevention")
EBSCO	(construction OR engineering) AND ((cognitive OR mental OR behavioural OR behavioral) AND (bias*)) AND ("safety management" OR "health and safety" OR "risk assessment" OR "risk perception" OR "risk management" OR "decision-making" OR "decision making" OR "occupational risks" OR "wellbeing" OR "well-being" OR "accident prevention")

Secondly, the search results were filtered to enhance the relevance and quality of the studies included in the review. As shown in Table 2, filters were applied to focus on peer-reviewed journal and conference papers published between 2018 and 2024, written in English, and related to the construction industry. The selection of publications from 2018 to 2024 ensured that the research was based on the latest research on cognitive biases and H&S performance in the construction industry. The search was restricted to ensure recency in the literature that displayed the current industry practices. Additionally, only open-access articles were included to ensure full accessibility for analysis. Articles were excluded if they were published before 2018, not written in English, inaccessible, or unrelated to the research topic.

Table 2. Eligibility criteria for literature search.

Eligibility	Criteria
Inclusion	Published between 2018 and 2024 Peer-reviewed articles Open access
Exclusion	Not written in English Not related to the research topic Review papers

3.2. Screening Process

As illustrated in Figure 1, 283 articles were initially identified using the specified search keywords and filters across three databases: 133 articles from Scopus, 20 from ScienceDirect, and 130 from EBSCO. These articles were imported into the EndNote 21 application and organised into three groups: Identification, Full-Text Screening, and Included. The selection process followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, completeness, and accuracy in the review [29].

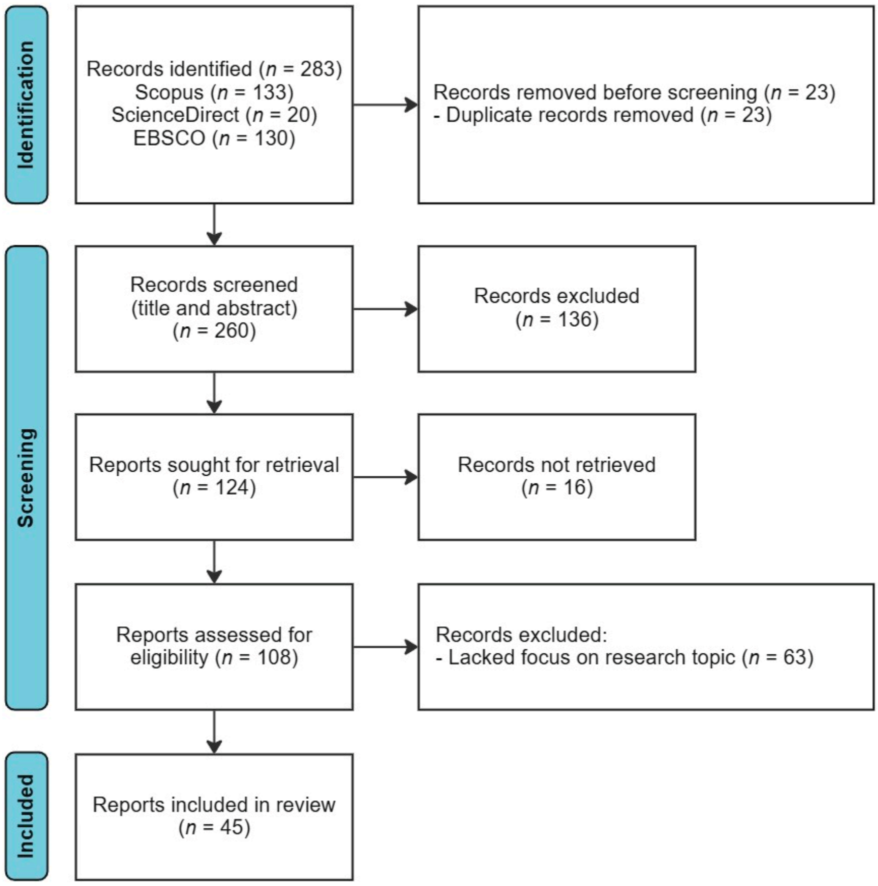


Figure 1. Literature selection process.

During the Identification phase, 23 duplicate articles were removed, leaving 260 articles for title and abstract screening. At this stage, 136 articles were excluded for failing to meet the inclusion criteria related to the research topic, resulting in 124 articles being selected for full-text retrieval via Google Scholar. Of these, 16 articles were inaccessible, leaving 108 records for the next phase. All 108 articles were thoroughly reviewed in the Full-Text Screening phase to ensure relevance. Sixty-three articles that lacked a clear focus on the research topic were excluded. Ultimately, 45 articles were deemed suitable and included in this research.

3.3. Data Extraction

Then, the selected articles were imported into Google Sheets for detailed analysis after the screening phase. Google Sheets served as the primary tool for recording and organising data, encompassing both the bibliographic details of the articles and the extracted analysis information. Initially, the included articles were listed in a “Data” sheet, with columns capturing each article’s title, authors, and publication year. Additionally, the first author’s country for each article was identified and recorded in a separate column.

3.3.1. Key Factors

After listing the articles in the "Data" sheet, the next step involved identifying and documenting the key factors analysed in the articles. In this phase, the articles were reviewed again within the EndNote 21 application using a thematic analysis methodology. Relevant factors associated with the research topic were highlighted in EndNote and subsequently recorded in a new sheet in Google Sheets named Factors.

The "Factors" sheet was divided into three columns. The first column recorded the factor names, while the second column categorised each factor into one of five predefined themes: cognitive biases, decision-making, health, safety, and behavioural. Finally, the third column included automatically generated factor codes created using a Google Sheets formula.

The dropdown feature in Google Sheets was used for the Theme column to maintain input data consistency, with the dropdown values derived from a reference table containing the predefined themes, as shown in Figure 2. Each theme in the table was assigned a unique code, which was incorporated into the formula for generating the factor codes (Figure 3). The finalised format of the "Factors" sheet is displayed in Figure 4.

	A	B
1	**Theme**	**Code**
2	Cognitive Biases	COGB
3	Decision Making	DCMK
4	Health	HLTH
5	Safety	SFTY
6	Behavioural	BHVR

Figure 2. Theme–code mapping.

C2 ▾ fx =IF(B2:B="", "", VLOOKUP(B2:B, Option!$A$1:$B$13, 2, FALSE) & "-" & TEXT(COUNTIF(B$2:B2, B2:B), "00"))

	A	B	C	N	O
1	**Name**	**Theme**	**Code**		
2	Ambiguity	Behavioural	BHVR-01		
3	Ambivalence	Behavioural	BHVR-02		
26	Affect Bias	Cognitive Biases	COGB-01		
27	Ambiguity Effect/Aversion	Cognitive Biases	COGB-02		

Figure 3. Generated factor code formula example.

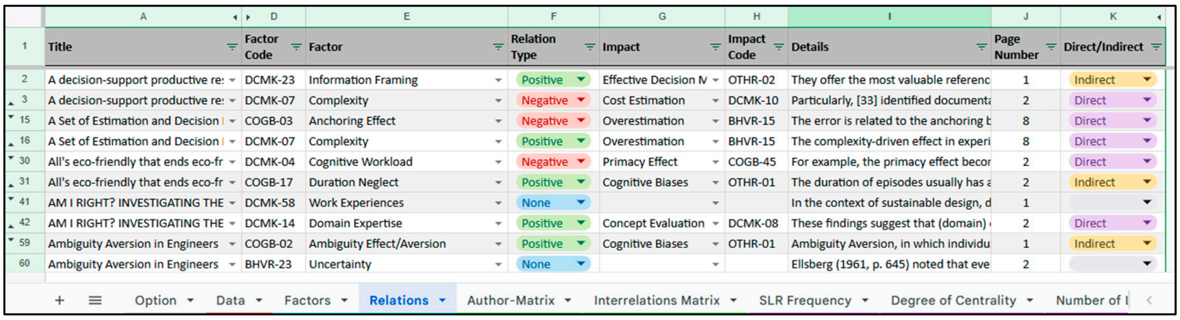
	A	B	C
1	**Name**	**Theme**	**Code**
2	Ambiguity	Behavioural	BHVR-01
3	Ambivalence	Behavioural	BHVR-02
26	Affect Bias	Cognitive Biases	COGB-01
27	Ambiguity Effect/Aversion	Cognitive Biases	COGB-02
28	Anchoring Effect	Cognitive Biases	COGB-03
29	Attentional Bias	Cognitive Biases	COGB-04
90	Chain of Command	Decision Making	DCMK-01
91	Cognitive Demand	Decision Making	DCMK-02
92	Cognitive Resources	Decision Making	DCMK-03
93	Cognitive Workload	Decision Making	DCMK-04
94	Communication & Collaboration	Decision Making	DCMK-05

\+ ≡ Option ▾ Data ▾ **Factors ▾** Relations ▾ Au

Figure 4. Table format of Factors sheet.

3.3.2. Interrelations

The relationships between factors were recorded and organised in a "Relations" sheet, with its format captured in Figure 5. Similarly to in the "Factors" sheet, dropdown menus were extensively utilised in this sheet to ensure data consistency. As shown in Figure 5, the columns employing dropdown menus included the Title, Factor, Relation Type, Impact, and Direct/Indirect columns. Detailed explanations for each column are provided in Table 3. Systematically organising the data in this table was a critical step for further analysis in this study.



	Title	Factor Code	Factor	Relation Type	Impact	Impact Code	Details	Page Number	Direct/Indirect
2	A decision-support productive re:	DCMK-23	Information Framing	Positive	Effective Decision M	OTHR-02	They offer the most valuable referenc	1	Indirect
3	A decision-support productive re:	DCMK-07	Complexity	Negative	Cost Estimation	DCMK-10	Particularly, [33] identified document:	2	Direct
15	A Set of Estimation and Decision I	COGB-03	Anchoring Effect	Negative	Overestimation	BHVR-15	The error is related to the anchoring b	8	Direct
16	A Set of Estimation and Decision I	DCMK-07	Complexity	Positive	Overestimation	BHVR-15	The complexity-driven effect in experi	8	Direct
30	All's eco-friendly that ends eco-fr	DCMK-04	Cognitive Workload	Negative	Primacy Effect	COGB-45	For example, the primacy effect becor	2	Direct
31	All's eco-friendly that ends eco-fr	COGB-17	Duration Neglect	Positive	Cognitive Biases	OTHR-01	The duration of episodes usually has a	2	Indirect
41	AM I RIGHT? INVESTIGATING THE	DCMK-58	Work Experiences	None			In the context of sustainable design, d	1	
42	AM I RIGHT? INVESTIGATING THE	DCMK-14	Domain Expertise	Positive	Concept Evaluation	DCMK-08	These findings suggest that (domain)	2	Direct
59	Ambiguity Aversion in Engineers	COGB-02	Ambiguity Effect/Aversion	Positive	Cognitive Biases	OTHR-01	Ambiguity Aversion, in which individu	1	Indirect
60	Ambiguity Aversion in Engineers	BHVR-23	Uncertainty	None			Ellsberg (1961, p. 645) noted that eve	2	

Figure 5. Table format of relations Excel sheet.

Table 3. Data types in "Relations" sheet table.

Column	Data Type	Values
Title	Dropdown	List of article titles from the "Data" sheet
Factor Code	Automated	Auto-assigned based on the selected factor
Factor	Dropdown	List of predefined factors from the "Factors" sheet
Relation Type	Dropdown	Positive/negative/none
Impact	Dropdown	List of predefined factors from the "Factors" sheet
Impact Code	Automated	Auto-assigned based on the selected impact
Details	Text	Extracted sentence from the article mentioning the relationship
Page Number	Number	Page number from the article where the relationship was found
Direct/Indirect	Dropdown	Direct/indirect

Similarly to in the key factors' identification, sentences in the articles that mentioned relationships between factors were highlighted using the highlighting feature in EndNote. These sentences were then documented in the "Relations" sheet. Firstly, the title of the article the sentence was from was chosen, and the sentence was recorded in the Details column to make it easy to revise and revisit, along with the corresponding page number in the next column.

The relationships between factors were then manually analysed to determine whether they represented positive or negative relations. A positive relation indicates that the factor contributes to a desirable or beneficial outcome regarding the impact, enhancing, facilitating, or supporting its improvement or effectiveness. For example, the relationship "Information Framing → Effective Decision Making" demonstrates how the strategic presentation of information can enhance decision-making effectiveness, while "Management Commitment → Productivity" highlights how strong leadership and management commitment can foster productivity. Conversely, a negative relation signifies that the factor has an undesirable or detrimental effect on the impact, hindering, reducing, or adversely influencing the performance or quality of the affected factor. For instance, the relationship "Complexity → Cost Estimation" illustrates how increased complexity can impair the accuracy of cost projections, while "Uncertainty → Productivity" shows how uncertainty negatively impacts productivity by causing confusion, delays, or inefficiencies.

In the Relation Type column, the value none indicates cases where an article discusses a particular factor but does not mention any specific interplay or relationship between that factor and others. By assigning the value none, it is made clear that the factor is acknowledged or highlighted in the article. However, no direct or indirect relationships with other factors are explicitly or implicitly addressed. Assigning this value ensured that all relevant mentions of factors were recorded even without interrelations, enabling a comprehensive and systematic research data analysis.

3.4. Data Analysis

Once the factor and interrelations data were systematically organised in Google Sheets, a series of programs were developed to automate the analysis process, minimising manual effort. These programs were implemented using Google Apps Script, Python 3.12.0, and JavaScript version 8 to ensure the efficient and accurate generation of analytical results. Figure 6 illustrates this study's overall analysis procedure and the tools utilised to produce the results.

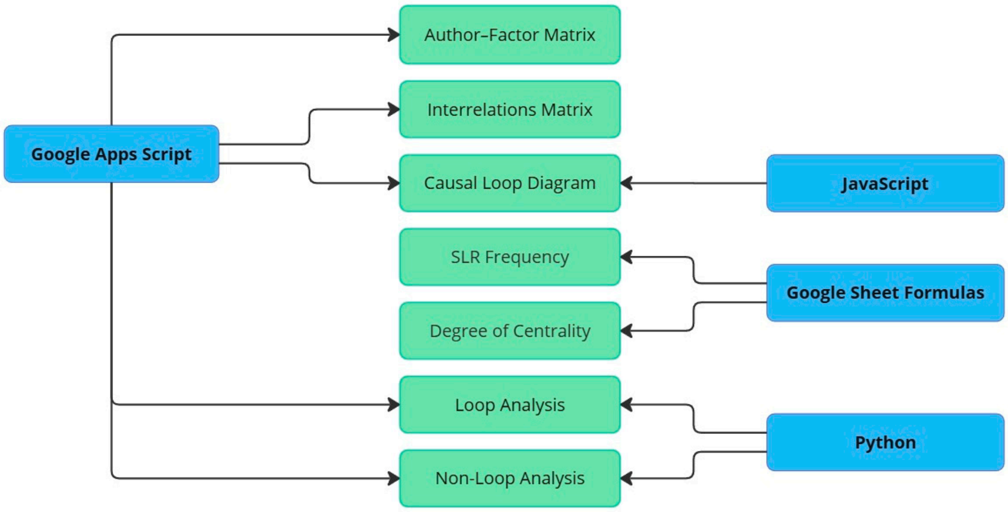
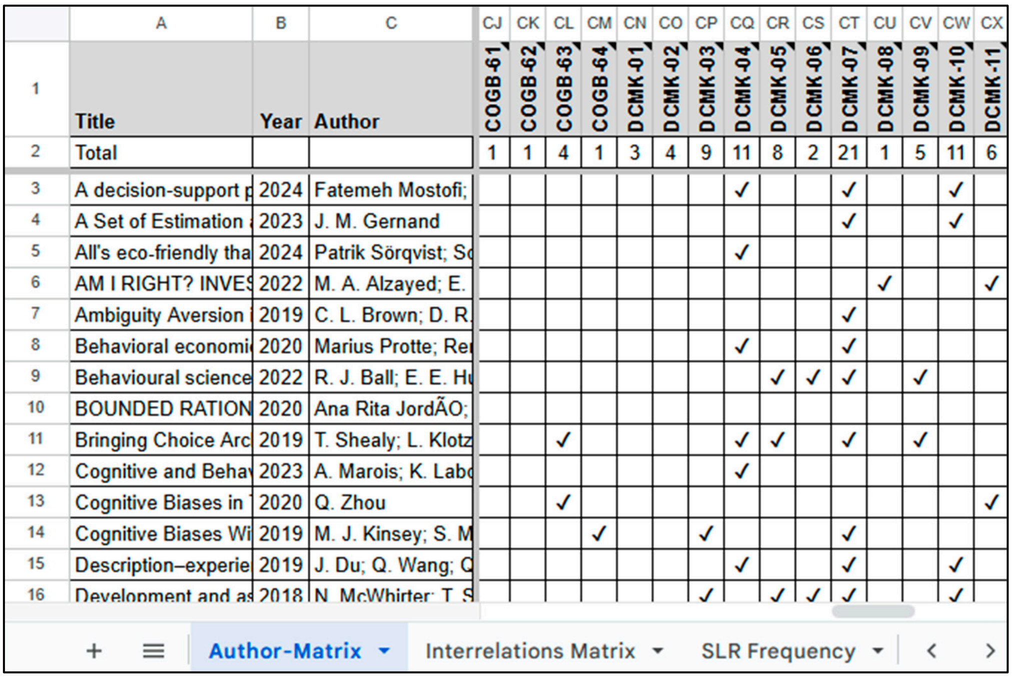


Figure 6. Data processing framework.

3.4.1. Author–Factor Matrix Generation

In generating the author–factor matrix, the program first accessed the "Factors" sheet to retrieve factor codes, which were then used as headers in a new "Author-Matrix" sheet. Next, it accessed the "Data" sheet to compile a list of authors, populating the first column of the matrix. Once the headers and the first column were generated, the program scanned the "Relations" sheet to identify specific factors in each article. The script examined each entry in the "Relations" sheet to determine whether an article was associated with a particular factor and marked the corresponding cell as true if a match was found. This process automatically populated the author–factor matrix, where a checkmark (✓) was placed in the appropriate cell when an article included a specific factor, as illustrated in Figure 7. Additionally, the program calculated the number of articles referencing each factor and recorded this count under the respective header in the second row. These numbers were subsequently used to determine the SLR frequency ranking, which is explained in a later section.

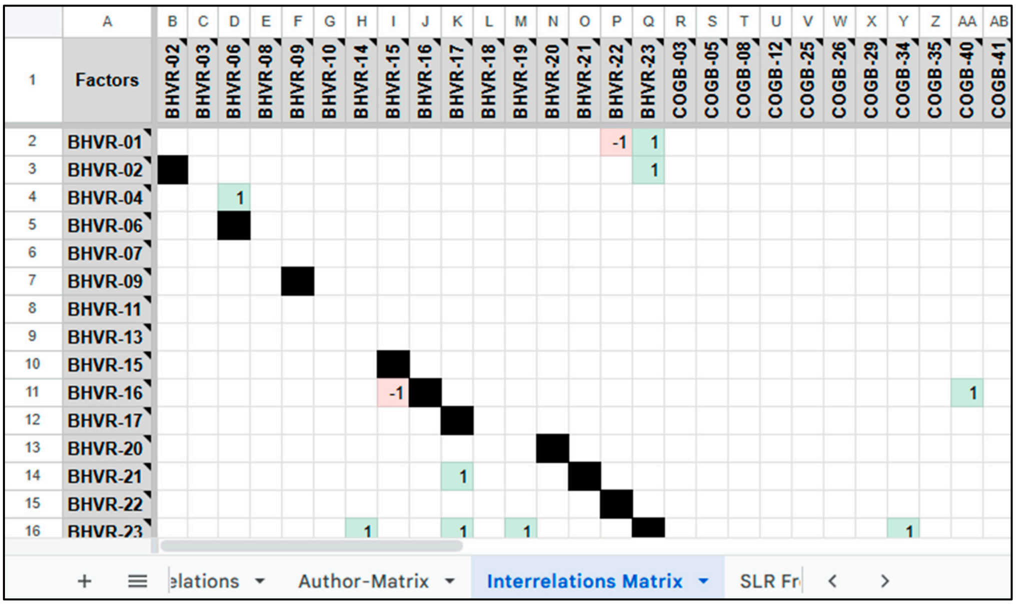


	A	B	C	CJ	CK	CL	CM	CN	CO	CP	CQ	CR	CS	CT	CU	CV	CW	CX
1	Title	Year	Author	COGB-61	COGB-62	COGB-63	COGB-64	DCMK-01	DCMK-02	DCMK-03	DCMK-04	DCMK-05	DCMK-06	DCMK-07	DCMK-08	DCMK-09	DCMK-10	DCMK-11
2	Total			1	1	4	1	3	4	9	11	8	2	21	1	5	11	6
3	A decision-support p	2024	Fatemeh Mostofi;								✓			✓			✓	
4	A Set of Estimation	2023	J. M. Gernand											✓			✓	
5	All's eco-friendly tha	2024	Patrik Sörqvist; Sc								✓							
6	AM I RIGHT? INVES	2022	M. A. Alzayed; E.												✓			✓
7	Ambiguity Aversion	2019	C. L. Brown; D. R.											✓				
8	Behavioral economi	2020	Marius Protte; Rei								✓			✓				
9	Behavioural science	2022	R. J. Ball; E. E. Hu									✓	✓	✓		✓		
10	BOUNDED RATION	2020	Ana Rita JordÃO;															
11	Bringing Choice Arc	2019	T. Shealy; L. Klotz			✓					✓	✓		✓		✓		
12	Cognitive and Beha	2023	A. Marois; K. Labc								✓							
13	Cognitive Biases in	2020	Q. Zhou			✓												✓
14	Cognitive Biases Wi	2019	M. J. Kinsey; S. M				✓			✓				✓				
15	Description–experie	2019	J. Du; Q. Wang; Q								✓			✓			✓	
16	Development and as	2018	N. McWhirter; T. S							✓		✓	✓	✓			✓	

Figure 7. Screenshot of the generated author–factor matrix [13,19,21,30–40].

3.4.2. Interrelation Matrix Generation

The generation of the interrelation matrix followed a similar process to that of the author–factor matrix. The program first accessed the "Factors" sheet to populate the first row and the first column of the matrix with the corresponding factor codes. It then iterated through each entry in the "Relations" sheet to calculate the matrix values. For each relationship, a positive relation incremented the corresponding value by 1, while a negative relation decremented it by 1. Once all values were calculated, the script removed rows and columns without any interrelations to enhance the matrix's readability. Additionally, positive values were highlighted in green, negative values in red, and diagonal cells where a factor related to itself were marked with a black background. The final interrelations matrix is illustrated in Figure 8.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	Factors	BHVR-02	BHVR-03	BHVR-06	BHVR-08	BHVR-09	BHVR-10	BHVR-14	BHVR-15	BHVR-16	BHVR-17	BHVR-18	BHVR-19	BHVR-20	BHVR-21	BHVR-22	BHVR-23	COGB-03	COGB-05	COGB-08	COGB-12	COGB-25	COGB-26	COGB-29	COGB-34	COGB-35	COGB-40	COGB-41
2	BHVR-01															-1	1											
3	BHVR-02																1											
4	BHVR-04			1																								
5	BHVR-06																											
6	BHVR-07																											
7	BHVR-09																											
8	BHVR-11																											
9	BHVR-13																											
10	BHVR-15																											
11	BHVR-16								-1																		1	
12	BHVR-17																											
13	BHVR-20																											
14	BHVR-21										1																	
15	BHVR-22																											
16	BHVR-23							1			1		1												1			

Figure 8. Screenshot of the generated interrelation matrix.

3.4.3. Causal Loop Diagram Generation

This study used the Vensim PLE Plus10.2.2 application to visualise a causal loop diagram (CLD), illustrating the interdependencies between the identified factors. However, manually creating variables and arrows in the diagram was time-consuming. To address this issue, a program was developed using Google Apps Script to automate the generation of Vensim files saved in the mdl format. The program iterated through the identified factors, considering them as variables, and generated connection arrows wherever relationships existed between factors. To optimise the layout and minimise overlapping elements, JavaScript libraries such as D3.js and WebCola were employed to calculate the positions of the diagram elements. This automated approach significantly reduced the time and effort required to construct the CLD from scratch. However, manual adjustments were still necessary to refine the visualisation, as the program's output lacked optimal visual clarity.

3.4.4. SLR Frequency Generation

The SLR frequency represents the number of articles referencing a particular factor, regardless of whether relationships between factors were identified. To obtain these data in a ranked format, the total counts recorded in the second row of the "Author-Matrix" sheet (see Figure 7) were extracted and imported into the "Factors" sheet using a formula. This formula retrieved the total value from the "Author-Matrix" sheet by matching the factor codes in both sheets. A pivot table was generated from the "Factors" sheet to visualise the SLR frequency effectively and enhance the clarity and presentation of the results. This study produced two SLR frequency rankings: one exclusively for the cognitive biases theme and another for the remaining themes. The final format of the SLR frequency rankings is illustrated in Figure 9.

	A	B	C	D	E	F	G
1	*Cognitive Bias*	SLR Frequency	Rank		*Factors*	SLR Frequency	Rank
2	Status Quo Bias	10	#1		Risk Perception	29	#1
3	Confirmation Bias	10	#1		Uncertainty	21	#2
4	Overconfidence Bias	9	#3		Complexity	21	#2
5	Optimism Bias	8	#4		Information Availability	16	#4
6	Anchoring Effect	8	#4		Work Experiences	14	#5
7	Loss Aversion	7	#6		Situational Awareness	13	#6
8	Availability Bias	6	#7		Psychological Disposition	13	#6
9	Group Think Bias	5	#8		Safety Training	12	#8
10	Sunk Cost Fallacy	4	#9		Risk Aversion	11	#9

\+ ≡ SLR Frequency ▾ Degree of Centrality ▾ Number of Loops ▾ Loop Cycle

Figure 9. Screenshot of SLR frequency pivot tables.

3.4.5. Degree of Centrality Calculation

Each factor's degree of centrality value was determined by calculating its out-degree and in-degree. To achieve this, a unique list of interrelations was created to eliminate duplications. This unique list was generated using Google Sheets formulas. First, a new column was added to the "Relations" sheet, where each entry in this column was automatically generated using a formula. If the Impact column was not empty, the formula combined the factor code, relation type, and impact code into a single text string. The formula used and an example of the resulting values are shown in Figure 10. Second, to ensure that duplicate links—caused by the exact same interrelation being mentioned in multiple articles—were removed, a unique formula was applied to this "Link" column in a separate sheet, as illustrated in Figure 11. This process ensured the accuracy and integrity of the interrelation data used to compute the degree of centrality.

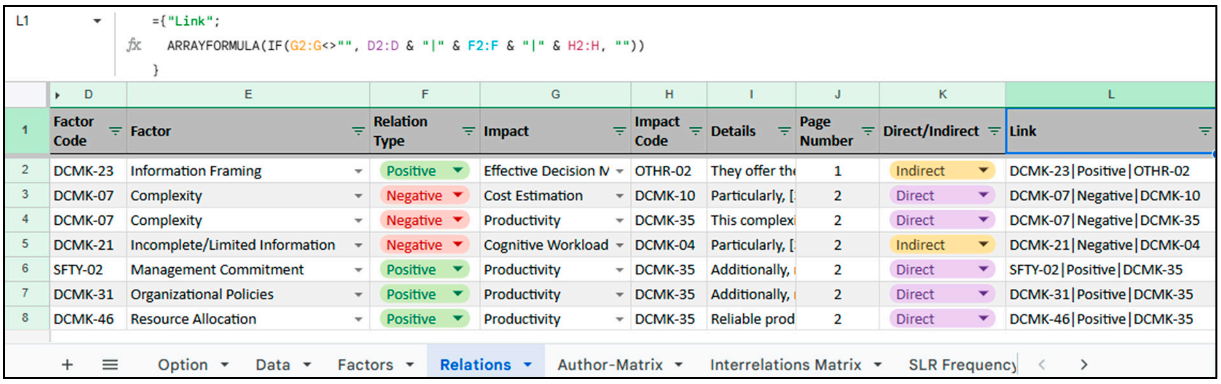


Figure 10. Formula to generate link code for each relation.

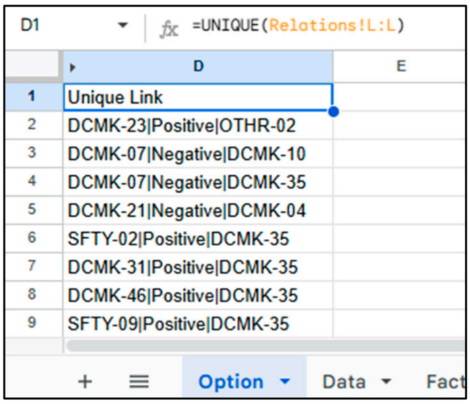


Figure 11. Formula to generate a unique link list to ensure no duplication.

The values required to calculate the degree of centrality were organised in the "Factors" sheet to ensure the data remained organised. The out-degree represents the number of connections a factor influences. To determine this, this study calculated the number of unique links where the respective factor code appeared as the prefix. Conversely, the in-degree represents the number of connections a factor receives, calculated by counting the unique links where the respective factor code appeared as the suffix. The formulas used for these calculations are shown in Figure 12.

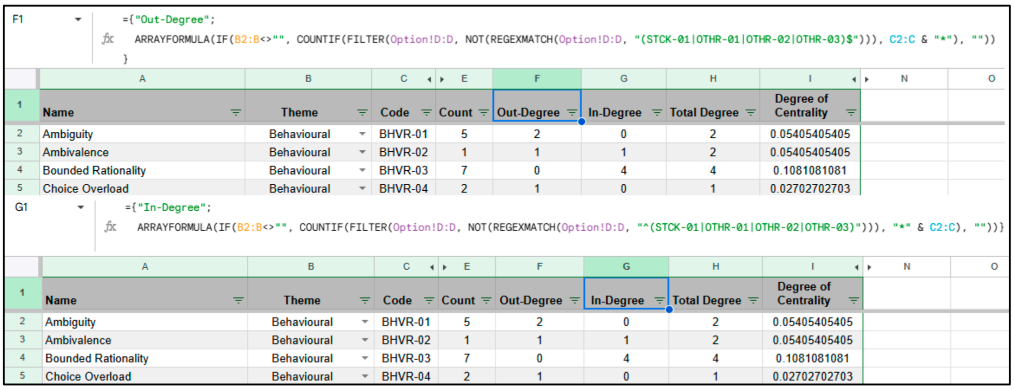
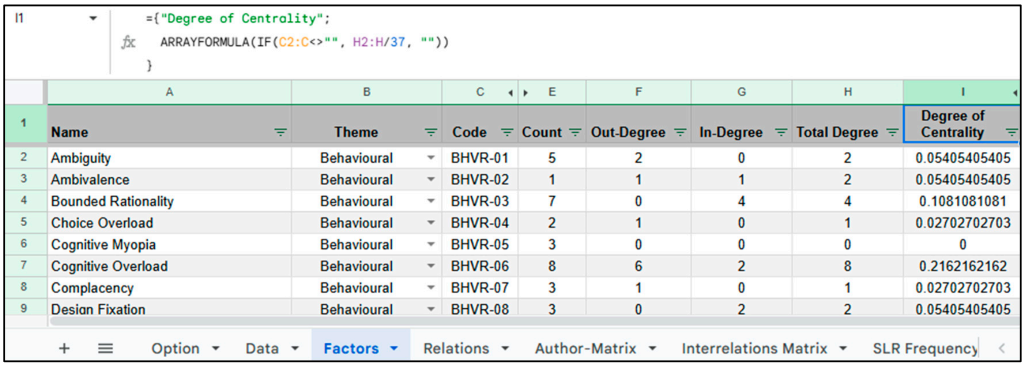


Figure 12. The formulas for out-degree and in-degree calculation.

Next to the in-degree column, an additional column was created to record the total degree of each factor, calculated as the sum of its out-degree and in-degree. Finally, the degree of centrality for each factor was calculated by dividing its total degree by the maximum total degree, which in this study was 37. The formula used to compute the degree of centrality is illustrated in Figure 13.



```
={"Degree of Centrality";
ARRAYFORMULA(IF(C2:C<>"", H2:H/37, ""))
}
```

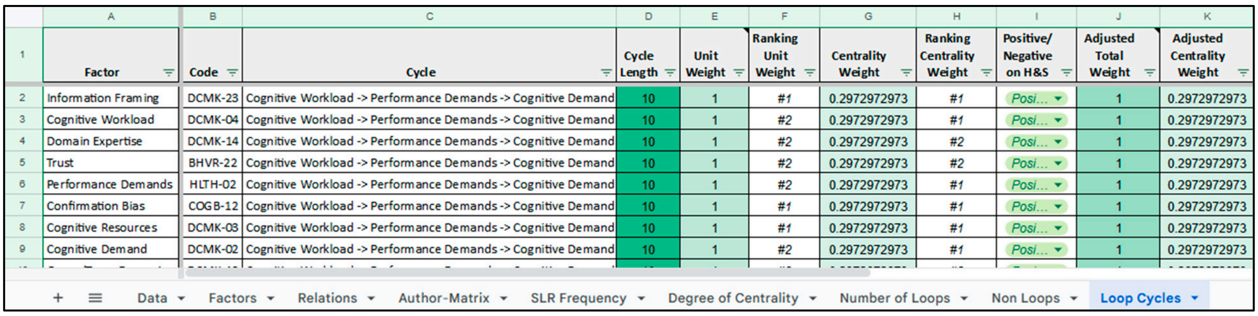
	Name	Theme	Code	Count	Out-Degree	In-Degree	Total Degree	Degree of Centrality
2	Ambiguity	Behavioural	BHVR-01	5	2	0	2	0.05405405405
3	Ambivalence	Behavioural	BHVR-02	1	1	1	2	0.05405405405
4	Bounded Rationality	Behavioural	BHVR-03	7	0	4	4	0.1081081081
5	Choice Overload	Behavioural	BHVR-04	2	1	0	1	0.02702702703
6	Cognitive Myopia	Behavioural	BHVR-05	3	0	0	0	0
7	Cognitive Overload	Behavioural	BHVR-06	8	6	2	8	0.2162162162
8	Complacency	Behavioural	BHVR-07	3	1	0	1	0.02702702703
9	Design Fixation	Behavioural	BHVR-08	3	0	2	2	0.05405405405

Figure 13. Formula to calculate the degree of centrality of each factor.

3.4.6. Loop Cycles

In this research, a Python program was developed to efficiently calculate the number of loops and loop cycles, reducing the time and effort required for manual analysis. The program utilised the built-in library Networkx, which provides functions to identify loops when the relationships between nodes are supplied. Alternatively, the Vensim application's loops menu can also obtain loop data. The results were cross-verified to ensure the program's accuracy compared to that of the results generated by Vensim.

After identifying the loop cycles, the data were imported into a new sheet titled "Loop Cycles." For each cycle, the total weight was calculated based on the relation type and the degree of centrality by creating an additional script using Google Apps Script. Unit weights were calculated based on the relation type, assigned as 1 for positive and −1 for negative relations. Weights based on the degree of centrality used the respective factor's degree of centrality value. Finally, due to the nature of the relationships in this research, each cycle was analysed and categorised as having either a positive or negative impact on H&S. For cycles with a positive impact, the absolute values of the total weight and degree of centrality weight were multiplied by 1. Conversely, the absolute values were multiplied by −1 for cycles with a negative impact. This approach ensured that higher positive values represented a more substantial positive impact on H&S, while lower negative values indicated a more significant negative impact. The final format of the "Loop Cycles" sheet is shown in Figure 14.

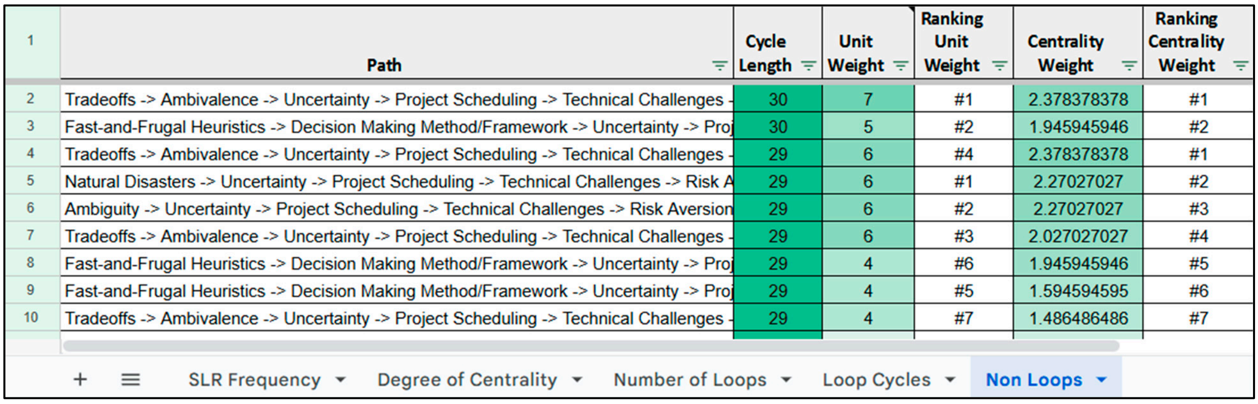


	Factor	Code	Cycle	Cycle Length	Unit Weight	Ranking Unit Weight	Centrality Weight	Ranking Centrality Weight	Positive/ Negative on H&S	Adjusted Total Weight	Adjusted Centrality Weight
2	Information Framing	DCMK-23	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#1	0.2972972973	#1	Posi...	1	0.2972972973
3	Cognitive Workload	DCMK-04	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#2	0.2972972973	#1	Posi...	1	0.2972972973
4	Domain Expertise	DCMK-14	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#2	0.2972972973	#2	Posi...	1	0.2972972973
5	Trust	BHVR-22	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#2	0.2972972973	#2	Posi...	1	0.2972972973
6	Performance Demands	HLTH-02	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#2	0.2972972973	#1	Posi...	1	0.2972972973
7	Confirmation Bias	COGB-12	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#1	0.2972972973	#1	Posi...	1	0.2972972973
8	Cognitive Resources	DCMK-03	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#1	0.2972972973	#1	Posi...	1	0.2972972973
9	Cognitive Demand	DCMK-02	Cognitive Workload -> Performance Demands -> Cognitive Demand	10	1	#2	0.2972972973	#1	Posi...	1	0.2972972973

Figure 14. Screenshot of the generated loop cycle analysis.

3.4.7. Critical Paths Generation

Similarly to in the process for identifying loop cycles, a Python program was developed to calculate the number of non-loop paths using the NetworkX library. The resulting data were imported into a new "Non Loops" sheet, where the unit and degree of centrality weights were calculated using a similar script implemented in Google Apps Script. As shown in Figure 15, the primary difference in this process was the absence of a flag to indicate whether a path had a positive or negative impact on H&S. This was due to the extensive volume of data and the fact that each path may have exhibited a mixed impact depending on its connections.



1	Path	Cycle Length	Unit Weight	Ranking Unit Weight	Centrality Weight	Ranking Centrality Weight
2	Tradeoffs -> Ambivalence -> Uncertainty -> Project Scheduling -> Technical Challenges -	30	7	#1	2.378378378	#1
3	Fast-and-Frugal Heuristics -> Decision Making Method/Framework -> Uncertainty -> Proj	30	5	#2	1.945945946	#2
4	Tradeoffs -> Ambivalence -> Uncertainty -> Project Scheduling -> Technical Challenges -	29	6	#4	2.378378378	#1
5	Natural Disasters -> Uncertainty -> Project Scheduling -> Technical Challenges -> Risk A	29	6	#1	2.27027027	#2
6	Ambiguity -> Uncertainty -> Project Scheduling -> Technical Challenges -> Risk Aversion	29	6	#2	2.27027027	#3
7	Tradeoffs -> Ambivalence -> Uncertainty -> Project Scheduling -> Technical Challenges -	29	6	#3	2.027027027	#4
8	Fast-and-Frugal Heuristics -> Decision Making Method/Framework -> Uncertainty -> Proj	29	4	#6	1.945945946	#5
9	Fast-and-Frugal Heuristics -> Decision Making Method/Framework -> Uncertainty -> Proj	29	4	#5	1.594594595	#6
10	Tradeoffs -> Ambivalence -> Uncertainty -> Project Scheduling -> Technical Challenges -	29	4	#7	1.486486486	#7

Figure 15. Screenshot of the generated non-loop path analysis.

3.5. Research Workflow

The research workflow presented in Figure 16 serves as the culmination of the methodological approach outlined in this study. It consolidates the sequential processes that guided the research, from identifying search keywords to the in-depth analysis of factors and relationships. Each step, from the systematic literature screening to data processing techniques, ensured a comprehensive exploration of decision factors and cognitive biases impacting construction H&S.

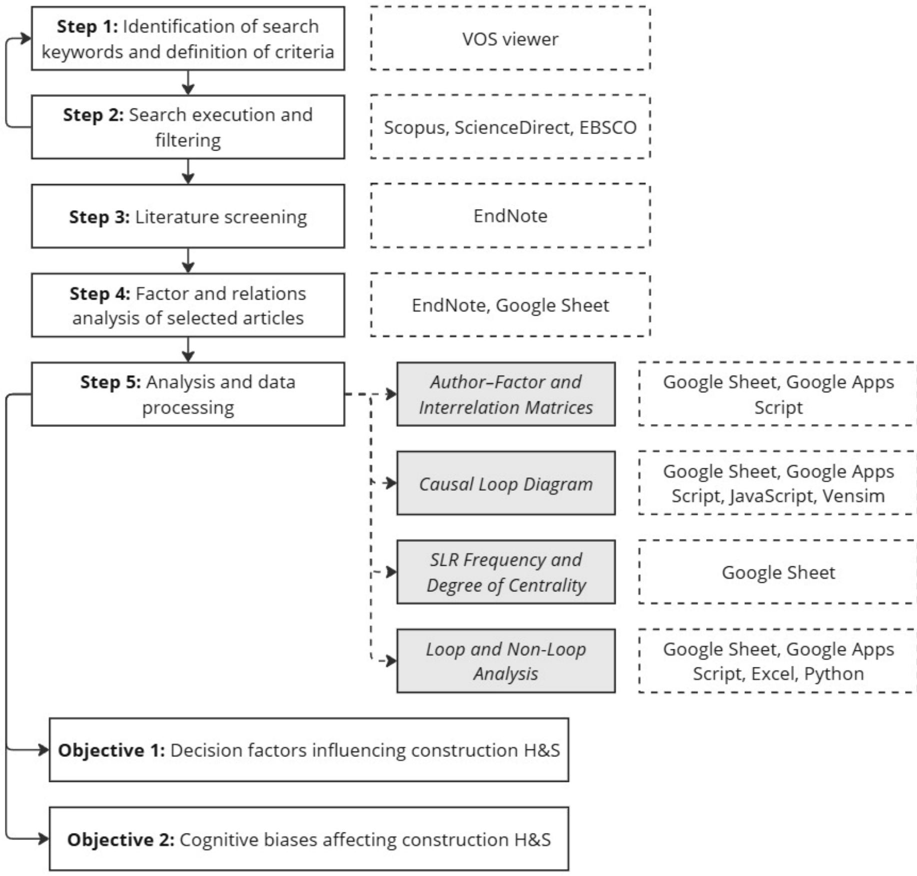


Figure 16. Research overview.

4. Results

This section presents the findings derived from the SLR. The results are structured according to various analytical approaches, including the distribution of publications, key factor identification, interrelations, and loop analysis. These analyses provide insights into patterns, dependencies, and relationships within the research topic, offering a comprehensive understanding of key influencing factors in construction H&S.

4.1. Distribution of Publications per Year

Figure 17 presents a stacked bar chart showing the number of publications per year from 2018 to 2024, categorised by country. The data indicate a peak in publications in 2019 and 2020, with nine articles each year, followed by a sharp decline in 2021. However, the trend shows a gradual recovery from 2022 onwards, with six publications recorded in 2023 and 2024. The distribution also highlights the contributions from various countries, with the United States consistently contributing the highest number of articles, accounting for 42.2% of the total publications, followed by China at 13.3%. Other countries, including Germany, Sweden, Australia, and the United Kingdom, each accounted for smaller proportions, reflecting a globally distributed research interest. The diversity of the contributing countries indicates the widespread recognition of the importance of this study's subject matter, reinforcing its global relevance.

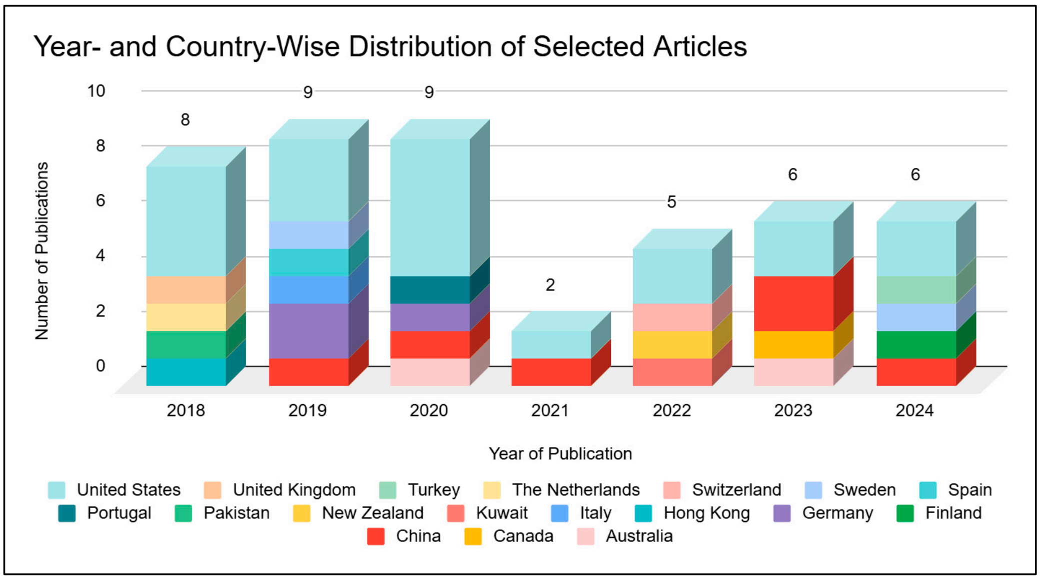


Figure 17. Year- and country-wise distribution of selected articles.

4.2. Factors and Cognitive Biases Identified in the Study

Identifying key influencing factors is critical to understanding decision-making in the construction sector. Table 4 categorises 100 identified factors into behavioural, health, safety, and decision-making aspects, highlighting their respective roles in shaping safety-related outcomes. Ambiguity, bounded rationality, and risk aversion illustrate the psychological and cognitive barriers to effective decision-making. Meanwhile, physical fatigue, unsafe behaviours, and the cognitive workload highlight systemic challenges in ensuring optimal safety performance.

Table 4. List of factors influencing decision-making.

No.	Factor	Code
1	Ambiguity	BHVR-01
2	Ambivalence	BHVR-02
3	Bounded Rationality	BHVR-03
4	Choice Overload	BHVR-04
5	Cognitive Myopia	BHVR-05
6	Cognitive Overload	BHVR-06
7	Complacency	BHVR-07
8	Design Fixation	BHVR-08
9	Empathic Concern	BHVR-09
10	Evaluation Apprehension	BHVR-10
11	Fast and Frugal Heuristics	BHVR-11
12	Hypovigilance	BHVR-12
13	Loss of Attention	BHVR-13
14	Optimizer's Curse	BHVR-14
15	Overestimation	BHVR-15
16	Risk Aversion	BHVR-16
17	Risk Propensity	BHVR-17
18	Sampling Errors Effect	BHVR-18
19	Satisficing	BHVR-19
20	Social Loafing	BHVR-20
21	Stress	BHVR-21
22	Trust	BHVR-22
23	Uncertainty	BHVR-23
24	Von Restorff Effect	BHVR-24
25	Chain of Command	DCMK-01
26	Cognitive Demand	DCMK-02
27	Cognitive Resources	DCMK-03
28	Cognitive Workload	DCMK-04
29	Communication and Collaboration	DCMK-05
30	Community Impact	DCMK-06
31	Complexity	DCMK-07
32	Concept Evaluation	DCMK-08
33	Cost	DCMK-09
34	Cost Estimation	DCMK-10
35	Creativity	DCMK-11
36	Decision-Making Method/Framework	DCMK-12
37	Distractions	DCMK-13
38	Domain Expertise	DCMK-14
39	Educational Level	DCMK-15
40	Emotions	DCMK-16
41	Feedback	DCMK-17
42	Government Regulations	DCMK-18
43	Group/Team Dynamics	DCMK-19
44	Heuristics	DCMK-20
45	Incomplete/Limited Information	DCMK-21
46	Information Availability	DCMK-22
47	Information Framing	DCMK-23
48	Information Overload	DCMK-24
49	Insider Perspective	DCMK-25
50	Institutional Pressures	DCMK-26
51	Lack of Trust	DCMK-27
52	Leadership	DCMK-28

Table 4. *Cont.*

No.	Factor	Code
53	Memory Processes	DCMK-29
54	Organisational Cultures	DCMK-30
55	Organisational Policies	DCMK-31
56	Outsider Perspective	DCMK-32
57	Passive Leadership	DCMK-33
58	Preferences	DCMK-34
59	Productivity	DCMK-35
60	Professional Backgrounds	DCMK-36
61	Professional Norms	DCMK-37
62	Project Approval	DCMK-38
63	Project Diversity	DCMK-39
64	Project Scheduling	DCMK-40
65	Psychological Disposition	DCMK-41
66	Psychological Distance	DCMK-42
67	Psychological Safety	DCMK-43
68	Reflective Evaluation	DCMK-44
69	Resistance to Change	DCMK-45
70	Resource Allocation	DCMK-46
71	Retrospective Evaluation	DCMK-47
72	Self-Evaluation	DCMK-48
73	Situational Awareness	DCMK-49
74	Social Norms	DCMK-50
75	Stakeholder Involvement	DCMK-51
76	Stimuli Modality	DCMK-52
77	Technical Challenges	DCMK-53
78	Time Availability	DCMK-54
79	Trade-Offs	DCMK-55
80	Transformational Leadership	DCMK-56
81	Visual Attention	DCMK-57
82	Work Experiences	DCMK-58
83	Workforce Diversity	DCMK-59
84	Climate Threat	HLTH-01
85	Performance Demands	HLTH-02
86	Physical Fatigue	HLTH-03
87	Time Pressure	HLTH-04
88	Construction Environment	SFTY-01
89	Management Commitment	SFTY-02
90	Natural Disasters	SFTY-03
91	Poor Working Environment	SFTY-04
92	Risk Assessment	SFTY-05
93	Risk Perception	SFTY-06
94	Risk Tolerance	SFTY-07
95	Safety Attitudes and Behaviours	SFTY-08
96	Safety Climate	SFTY-09
97	Safety Interventions	SFTY-10
98	Safety Standards	SFTY-11
99	Safety Training	SFTY-12
100	Unsafe Behaviours	SFTY-13

Table 5 presents a comprehensive list of 64 cognitive biases identified as impacting decision-making in construction. Among the most notable are confirmation bias, which reinforces pre-existing beliefs and hinders adaptability [30], and optimism bias, which may lead to underestimating potential hazards [15]. Additionally, status quo bias can lead decision-makers to favour existing conditions over necessary changes [13], potentially resulting in resistance to improved safety measures.

Table 5. List of cognitive biases.

No.	Cognitive Bias	Code	Description
1	Affect Bias	COGB-01	The tendency to let emotions, such as fear and pleasure, influence decisions [41]
2	Ambiguity Effect/Aversion	COGB-02	The tendency to prefer options where the outcome is known over those with an unknown outcome [41]
3	Anchoring Effect	COGB-03	The tendency to rely too heavily on the first piece of information encountered when making decisions [13]
4	Attentional Bias	COGB-04	The tendency to focus on specific pieces of information while ignoring others [31]
5	Authority Bias	COGB-05	The tendency to attribute greater accuracy and importance to the opinion of an authority figure, regardless of its validity [41]
6	Automation Bias	COGB-06	The tendency to over-rely on automated systems and technology [42]
7	Availability Bias	COGB-07	The tendency to be influenced by information that one can recall easily [43]
8	Bandwagon Effect	COGB-08	The tendency to adopt behaviours, beliefs, or trends simply because many others do the same [44]
9	Bystander Effect	COGB-09	The tendency to be less likely to help someone in distress when others are present, assuming someone else will take action [45]
10	Certainty Effect	COGB-10	The tendency to prefer outcomes that are certain over those that are merely probable [46]
11	Choice-Supportive Bias	COGB-11	The tendency to recall positive aspects more than negative ones when remembering past choices [47]
12	Confirmation Bias	COGB-12	The tendency to search for, interpret, and recall information in a way that confirms one's pre-existing beliefs [14]
13	Consequence Bias	COGB-13	The tendency to judge a decision based on its outcome rather than the process used to make it [48]
14	Courtesy Bias	COGB-14	The tendency to give socially desirable responses rather than honest opinions to avoid offending others [41]
15	Default Effect	COGB-15	The tendency to go with the default option [49]
16	Dunning–Kruger Effect	COGB-16	The tendency of people with low ability to overestimate their competence, while highly competent people underestimate their ability [50]
17	Duration Neglect	COGB-17	The tendency to disregard the duration of an experience and judge it only by the peak and end moments [51]
18	Fading Affect Bias	COGB-18	The tendency for negative events to be forgotten faster than positive ones [52]
19	False Consensus Bias	COGB-19	The tendency to overestimate how much others share one's beliefs, attitudes, and behaviours [41]
20	Fear of Missing Out	COGB-20	The tendency to experience anxiety over the possibility of missing out on pleasant experiences that others are having [53]
21	Focusing Effect	COGB-21	The tendency to place too much importance on one aspect of an event while ignoring others [54]
22	Framing Bias	COGB-22	The tendency for decisions to be influenced by the way information is presented rather than by the actual content [55]
23	Gender Bias	COGB-23	The tendency to favour one gender over another results in unequal treatment and stereotypes [56]
24	Group Polarisation	COGB-24	The tendency to adopt the majority opinion, regardless of supporting facts or evidence [52]
25	Group Think Bias	COGB-25	The tendency to align with a group to gain collective support [52]
26	Halo Effect	COGB-26	The tendency to let a single characteristic shape one's entire opinion, whether positively or negatively [41]
27	Hindsight Bias	COGB-27	The tendency to see past events as more predictable than they were after they have happened [57]

Table 5. *Cont.*

No.	Cognitive Bias	Code	Description
28	Hot Hand Fallacy	COGB-28	The tendency to believe that a person who has experienced success in a random event has a higher chance of future success [58]
29	Illusion of Control	COGB-29	The tendency to overestimate one's ability to control or affect events beyond one's influence [59]
30	Illusion of Truth Effect	COGB-30	The tendency to believe familiar statements over unfamiliar ones, regardless of their actual validity [41]
31	In-Group Bias	COGB-31	The tendency to favour members of one's group over outsiders [41]
32	Isolation Effect	COGB-32	The tendency to remember unique or distinctive items better than common ones [60]
33	Lemming Effect	COGB-33	The tendency to follow others mindlessly without evaluating potential risks or consequences [61]
34	Loss Aversion	COGB-34	The tendency to prefer avoiding risks even when potential gains outweigh the losses [46]
35	Mere Exposure Effect	COGB-35	The tendency to develop a preference for things merely because of repeated exposure to them [62]
36	Modality Effect	COGB-36	The tendency to have stronger memory retention for recently spoken items compared to written ones [41]
37	Negativity Bias	COGB-37	The tendency to pay more attention to negative experiences or information than positive ones [63]
38	Next-In-Line Effect	COGB-38	The tendency to experience diminished recall of prior speakers' words when waiting for one's turn to speak [41]
39	Normalcy Bias	COGB-39	The tendency to underestimate the possibility of disasters, assuming that things will continue as they always have [64]
40	Optimism Bias	COGB-40	The tendency to believe that positive events are more likely to happen to oneself while negative events are more likely to happen to others [31]
41	Overconfidence Bias	COGB-41	The tendency to overestimate one's knowledge, abilities, or judgement, leading to poor decision-making [65]
42	Ownership Bias	COGB-42	The tendency to overvalue objects simply because they belong to oneself [52]
43	Peak–End Rule	COGB-43	The tendency to judge experiences based on how they felt at their peak and end rather than their entire duration [51]
44	Planning Fallacy	COGB-44	The tendency to underestimate the time, costs, and risks associated with a task while overestimating the benefits [13]
45	Primacy Effect	COGB-45	The tendency to remember the first items in a list better than later items [66]
46	Priming Bias	COGB-46	The tendency to be influenced by prior stimuli in decision-making or behaviour without realising it [67]
47	Pseudo Certainty Effect	COGB-47	The tendency to assume certainty in situations where the outcome remains unpredictable [68]
48	Quantity Insensitivity	COGB-48	The tendency to underestimate the actual amount of an item when making decisions [46]
49	Recency Bias	COGB-49	The tendency to give greater weight to recent information than to earlier information [69]
50	Recency Effect	COGB-50	The tendency to remember the last items in a list better than earlier items [70]
51	Reflection Effect	COGB-51	The tendency to avoid risks when presented with potential gains but seek risks when faced with potential losses [46]
52	Representativeness	COGB-52	The tendency to judge probabilities based on how much something resembles a known category rather than on actual data [71]
53	Rhyme-as-Reason Bias	COGB-53	The tendency to believe that statements that rhyme are more truthful than those that do not [72]
54	Risk Compensation	COGB-54	The tendency to take greater risks when one feels more protected [73]
55	Rosy Retrospection	COGB-55	The tendency to remember past events as more positive than they actually were [41]

Table 5. *Cont.*

No.	Cognitive Bias	Code	Description
56	Routine	COGB-56	The tendency to favour familiar patterns of behaviour [74]
57	Self-Serving Bias	COGB-57	The tendency to attribute successes to personal factors while blaming failures on external factors [75]
58	Social Desirability Bias	COGB-58	The tendency to respond in ways that are viewed favourably by others rather than truthfully [76]
59	Spacing Bias	COGB-59	The tendency to retain information better when learning is spaced out over time [77]
60	Status Quo Bias	COGB-60	The tendency to prefer things to stay the same rather than change, even when alternatives may offer greater benefits [78]
61	Stereotyping	COGB-61	The tendency to make generalisations about people based on group characteristics rather than individual traits [41]
62	Summit Fever	COGB-62	The tendency to make irrational decisions near the completion of a goal due to heightened motivation [46]
63	Sunk Cost Fallacy	COGB-63	The tendency to continue an endeavour because of past investments rather than considering future costs and benefits [79]
64	Unit Bias	COGB-64	The tendency to view a single, complete unit—whether food, a task, or a product—as the appropriate amount, regardless of its actual size [80]

4.3. Author–Factor Matrix

The author–behavioural, safety, and health factors matrix summarises the factors discussed in various studies and links them to their respective authors, publication years, and countries. Each row represents a selected article, while each column corresponds to a specific factor relevant to decision-making in the construction sector. A checkmark (✓) in a cell indicates that the author addressed the corresponding factor. Similarly, the author–decision-making factor matrix and the author–cognitive bias matrix for the selected articles were generated and can be seen in Appendix A.

4.4. Interrelation Matrix

An interrelation matrix is an analytical tool that maps the interplay of decision-making factors, cognitive biases, and key behavioural, health, and safety factors. By analysing this matrix, we could identify patterns highlighting the relationships between different elements affecting H&S performance in the construction sector. The full interrelation matrix is shown in Appendix B.

4.5. Causal Loop Diagram

A causal loop diagram represents a deeper exploration into factor interactions, as illustrated in Figure 18. This visual model was created using the Vensim app to demonstrate feedback mechanisms in decision-making and H&S performance.

4.6. SLR Frequency

The SLR frequency analysis, the results of which are shown in Tables 6 and 7, ranked the prevalence of cognitive biases and decision-making factors in the research. Status quo bias (COGB-60), confirmation bias (COGB-12), and overconfidence bias (COGB-41) dominated the findings, emphasising how these biases affect decision-making. Similarly, risk perception (SFTY-06), complexity (DCMK-07), and uncertainty (BHVR-23) emerged as key influences in construction H&S performance.

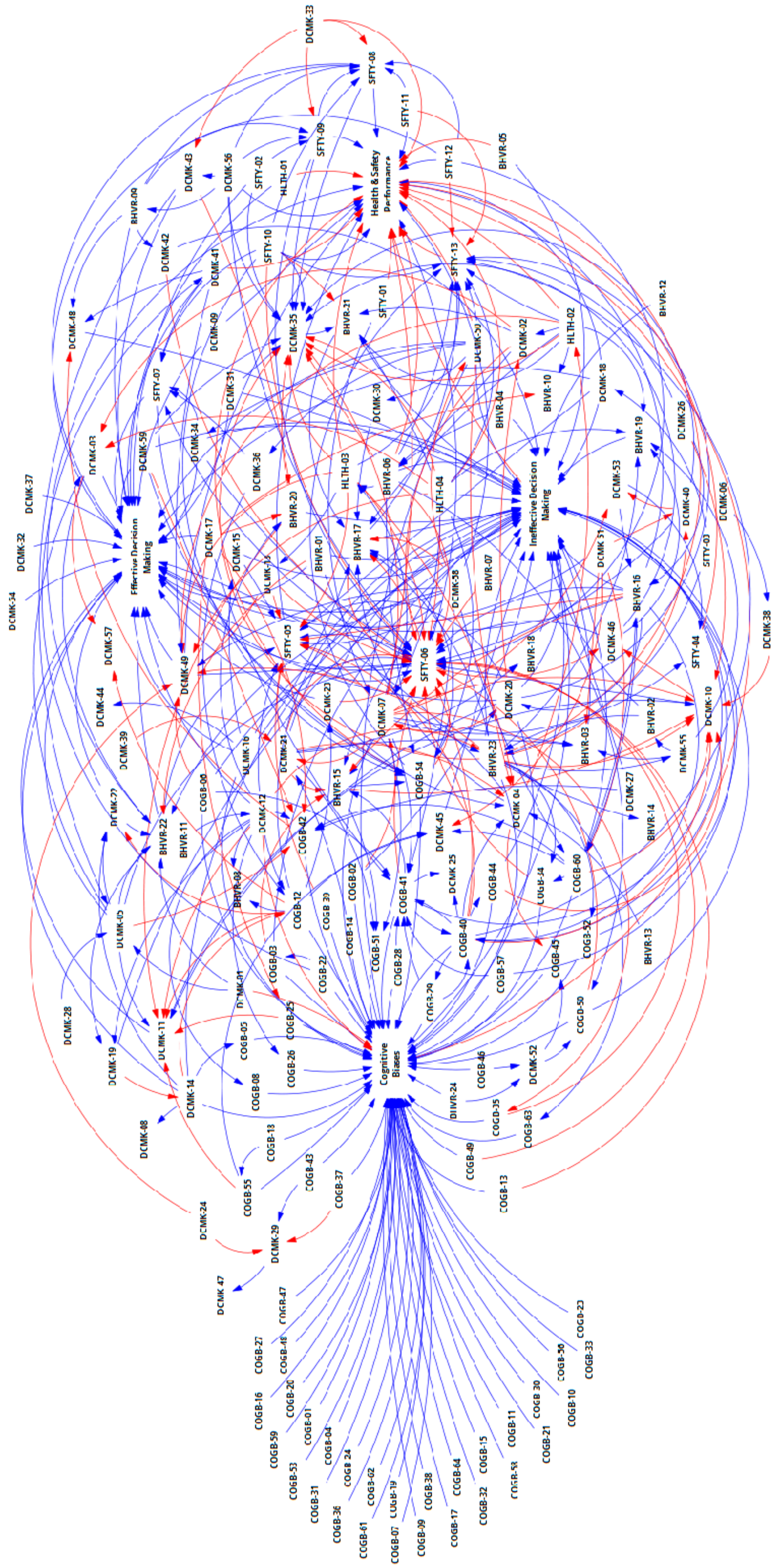


Figure 18. Causal loop diagram.

Table 6. SLR frequency ranking—cognitive biases.

Code	SLR Frequency	Rank
COGB-60	10	#1, #2
COGB-12	10	
COGB-41	9	#3
COGB-40	8	#4, #5
COGB-03	8	
COGB-34	7	#6
COGB-07	6	#7
COGB-25	5	#8
COGB-63	4	#9–#14
COGB-54	4	
COGB-29	4	
COGB-26	4	
COGB-22	4	
COGB-08	4	
COGB-52	3	#15–#19
COGB-44	3	
COGB-42	3	
COGB-27	3	
COGB-05	3	
COGB-58	2	#20–#29
COGB-57	2	
COGB-55	2	
COGB-51	2	
COGB-50	2	
COGB-49	2	
COGB-43	2	
COGB-16	2	
COGB-10	2	
COGB-02	2	
COGB-64	1	#30–#64
COGB-62	1	
COGB-61	1	
COGB-59	1	
COGB-56	1	
COGB-53	1	
COGB-48	1	
COGB-47	1	
COGB-46	1	
COGB-45	1	
COGB-39	1	
COGB-38	1	
COGB-37	1	
COGB-36	1	
COGB-35	1	
COGB-33	1	
COGB-32	1	
COGB-31	1	
COGB-30	1	

Table 6. *Cont.*

Code	SLR Frequency	Rank
COGB-28	1	#30–#64
COGB-24	1	
COGB-23	1	
COGB-21	1	
COGB-20	1	
COGB-19	1	
COGB-18	1	
COGB-17	1	
COGB-15	1	
COGB-14	1	
COGB-13	1	
COGB-11	1	
COGB-09	1	
COGB-06	1	
COGB-04	1	
COGB-01	1	

Table 7. SLR frequency ranking—factors.

Code	SLR Frequency	Rank
SFTY-06	29	#1
DCMK-07	21	#2, #3
BHVR-23	21	
DCMK-22	16	#4
DCMK-58	14	#5
DCMK-49	13	#6, #7
DCMK-41	13	
SFTY-12	12	#8
DCMK-10	11	#9–#11
DCMK-04	11	
BHVR-16	11	
SFTY-05	10	#12, #13
DCMK-14	10	
SFTY-13	9	#14–#22
SFTY-07	9	
HLTH-04	9	
HLTH-02	9	
DCMK-50	9	
DCMK-34	9	
DCMK-21	9	
DCMK-16	9	
DCMK-03	9	
SFTY-08	8	#23–#29
SFTY-01	8	
DCMK-40	8	
DCMK-23	8	
DCMK-20	8	
DCMK-05	8	
BHVR-06	8	

Table 7. *Cont.*

Code	SLR Frequency	Rank
DCMK-46	7	#30–#36
DCMK-35	7	
DCMK-15	7	
BHVR-22	7	
BHVR-17	7	
BHVR-15	7	
BHVR-03	7	
SFTY-10	6	#37–#40
SFTY-09	6	
DCMK-54	6	
DCMK-11	6	
SFTY-11	5	#41–#49
HLTH-03	5	
DCMK-59	5	
DCMK-51	5	
DCMK-45	5	
DCMK-12	5	
DCMK-09	5	
BHVR-19	5	
BHVR-01	5	
DCMK-31	4	#50–#56
DCMK-29	4	
DCMK-24	4	
DCMK-17	4	
DCMK-13	4	
DCMK-02	4	
BHVR-21	4	
SFTY-02	3	#57–#71
DCMK-56	3	
DCMK-55	3	
DCMK-53	3	
DCMK-43	3	
DCMK-42	3	
DCMK-39	3	
DCMK-36	3	
DCMK-26	3	
DCMK-19	3	
DCMK-18	3	
DCMK-01	3	
BHVR-08	3	
BHVR-07	3	
BHVR-05	3	
SFTY-03	2	#72–#85
HLTH-01	2	
DCMK-57	2	
DCMK-52	2	
DCMK-38	2	
DCMK-33	2	

Table 7. *Cont.*

Code	SLR Frequency	Rank
DCMK-32	2	#72–#85
DCMK-30	2	
DCMK-27	2	
DCMK-25	2	
DCMK-06	2	
BHVR-20	2	
BHVR-09	2	
BHVR-04	2	
SFTY-04	1	#86–#100
DCMK-48	1	
DCMK-47	1	
DCMK-44	1	
DCMK-37	1	
DCMK-28	1	
DCMK-08	1	
BHVR-24	1	
BHVR-18	1	
BHVR-14	1	
BHVR-13	1	
BHVR-12	1	
BHVR-11	1	
BHVR-10	1	
BHVR-02	1	

4.7. Degree of Centrality

A closer look at Table 8 reveals the most interconnected factors in decision-making. Risk perception (SFTY-06) ranked the highest, reflecting its fundamental role in shaping safety outcomes. Additionally, productivity (DCMK-35) and the cognitive workload (DCMK-07) are critical in understanding decision-making limitations. These centrality rankings provide insight into which factors should be prioritised for further analysis.

Table 8. Degree of centrality analysis.

Code	Total Degree	Degree of Centrality	Rank
SFTY-06	37	1.00000	#1
DCMK-35	17	0.45946	#2, #3
DCMK-07	17	0.45946	
BHVR-23	16	0.43243	#4
SFTY-05	15	0.40541	#5
SFTY-13	13	0.35135	#6
COGB-41	12	0.32432	#7, #8
COGB-40	12	0.32432	
DCMK-12	11	0.29730	#9–#11
DCMK-10	11	0.29730	
BHVR-17	11	0.29730	
DCMK-49	10	0.27027	#12, #13
DCMK-21	10	0.27027	

Table 8. *Cont.*

Code	Total Degree	Degree of Centrality	Rank
HLTH-04	9	0.24324	#14–#23
HLTH-03	9	0.24324	
HLTH-02	9	0.24324	
DCMK-58	9	0.24324	
DCMK-05	9	0.24324	
DCMK-04	9	0.24324	
COGB-54	9	0.24324	
COGB-12	9	0.24324	
BHVR-16	9	0.24324	
BHVR-15	9	0.24324	
SFTY-08	8	0.21622	#24–#28
DCMK-11	8	0.21622	
COGB-60	8	0.21622	
BHVR-22	8	0.21622	
BHVR-06	8	0.21622	
SFTY-10	7	0.18919	#29–#32
SFTY-09	7	0.18919	
DCMK-20	7	0.18919	
COGB-42	7	0.18919	
SFTY-07	6	0.16216	#33–#37
DCMK-56	6	0.16216	
DCMK-50	6	0.16216	
DCMK-02	6	0.16216	
BHVR-21	6	0.16216	
DCMK-46	5	0.13514	#38–#45
DCMK-40	5	0.13514	
DCMK-17	5	0.13514	
DCMK-14	5	0.13514	
DCMK-03	5	0.13514	
BHVR-20	5	0.13514	
BHVR-19	5	0.13514	
BHVR-09	5	0.13514	
DCMK-55	4	0.10811	#46–#57
DCMK-53	4	0.10811	
DCMK-52	4	0.10811	
DCMK-51	4	0.10811	
DCMK-45	4	0.10811	
DCMK-43	4	0.10811	
DCMK-41	4	0.10811	
DCMK-29	4	0.10811	
DCMK-22	4	0.10811	
DCMK-16	4	0.10811	
DCMK-13	4	0.10811	
BHVR-03	4	0.10811	
SFTY-12	3	0.08108	#58–#71
DCMK-59	3	0.08108	
DCMK-48	3	0.08108	
DCMK-36	3	0.08108	

Table 8. *Cont.*

Code	Total Degree	Degree of Centrality	Rank
DCMK-34	3	0.08108	#58–#71
DCMK-33	3	0.08108	
DCMK-26	3	0.08108	
DCMK-23	3	0.08108	
DCMK-19	3	0.08108	
COGB-55	3	0.08108	
COGB-51	3	0.08108	
COGB-50	3	0.08108	
COGB-34	3	0.08108	
COGB-29	3	0.08108	
SFTY-11	2	0.05405	#72–#95
SFTY-04	2	0.05405	
SFTY-03	2	0.05405	
SFTY-02	2	0.05405	
DCMK-57	2	0.05405	
DCMK-42	2	0.05405	
DCMK-38	2	0.05405	
DCMK-30	2	0.05405	
DCMK-25	2	0.05405	
DCMK-24	2	0.05405	
DCMK-18	2	0.05405	
DCMK-15	2	0.05405	
DCMK-01	2	0.05405	
COGB-45	2	0.05405	
COGB-44	2	0.05405	
COGB-35	2	0.05405	
COGB-25	2	0.05405	
COGB-22	2	0.05405	
COGB-06	2	0.05405	
COGB-03	2	0.05405	
BHVR-10	2	0.05405	
BHVR-08	2	0.05405	
BHVR-02	2	0.05405	
BHVR-01	2	0.05405	
SFTY-01	1	0.02703	#96–#127
DCMK-47	1	0.02703	
DCMK-44	1	0.02703	
DCMK-39	1	0.02703	
DCMK-31	1	0.02703	
DCMK-28	1	0.02703	
DCMK-27	1	0.02703	
DCMK-08	1	0.02703	
DCMK-06	1	0.02703	
COGB-63	1	0.02703	
COGB-57	1	0.02703	
COGB-52	1	0.02703	
COGB-49	1	0.02703	
COGB-46	1	0.02703	

Table 8. *Cont.*

Code	Total Degree	Degree of Centrality	Rank
COGB-43	1	0.02703	#96–#127
COGB-39	1	0.02703	
COGB-37	1	0.02703	
COGB-28	1	0.02703	
COGB-26	1	0.02703	
COGB-18	1	0.02703	
COGB-14	1	0.02703	
COGB-13	1	0.02703	
COGB-08	1	0.02703	
COGB-05	1	0.02703	
COGB-02	1	0.02703	
BHVR-24	1	0.02703	
BHVR-18	1	0.02703	
BHVR-14	1	0.02703	
BHVR-13	1	0.02703	
BHVR-11	1	0.02703	
BHVR-07	1	0.02703	
BHVR-04	1	0.02703	

4.8. Loop Analysis

Table 9 presents the Number of Loops Ranking, highlighting the most frequently occurring feedback loops in decision-making and safety performance.

Table 9. Factor—Number of Loops Ranking.

Code	Number of Loops	Rank
SFTY-06	6	#1
DCMK-14	3	#2–#6
COGB-40	3	
BHVR-22	3	
BHVR-17	3	
DCMK-19	3	
DCMK-04	2	#7–#17
DCMK-46	2	
BHVR-16	2	
DCMK-22	2	
COGB-41	2	
COGB-29	2	
SFTY-07	2	
HLTH-02	2	
COGB-12	2	
DCMK-02	2	
COGB-54	2	
DCMK-23	1	#18–#31
DCMK-07	1	
DCMK-35	1	
BHVR-23	1	
SFTY-05	1	

Table 9. *Cont.*

Code	Number of Loops	Rank
COGB-60	1	#18–#31
DCMK-20	1	
BHVR-06	1	
BHVR-21	1	
DCMK-53	1	
DCMK-55	1	
DCMK-03	1	
HLTH-03	1	
BHVR-02	1	

Loop cycle analysis, the results of which are shown in Table 10, further examined how these loops were interconnected, illustrating how interdependent factors continuously shape decision-making processes. Two key metrics were calculated to quantify the influence of each loop: the unit weight and centrality weight. The unit weight of a loop was determined by evaluating the nature of each connection within the cycle. If the relationship between two factors was positive, it contributed +1 to the total unit weight, and if the relationship was negative, it contributed −1. The centrality weight was calculated similarly, but instead of using a contribution of +1/−1 based on the relation types, the calculation incorporated the degree of centrality of each factor in the loop. By analysing these weights, this study identified which loops exerted the most significant influence, helping to prioritise areas for intervention in construction H&S management.

Table 10. Results of loop cycle analysis.

No.	Cycle	Positive/Negative Impact on H&S	Unit Weight	Rank Unit Weight	Centrality Weight	Rank Centrality Weight
1	SFTY-05 → SFTY-06 → SFTY-05	Positive	2	#1–#3	1.405405405	#1
2	BHVR-16 → COGB-60 → BHVR-16	Positive	2		0.4594594595	#3
3	DCMK-14 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14	Positive	2		0.3783783784	#4
4	DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23	Positive	1	#4, #5	0.2972972973	#5
5	DCMK-14 → COGB-12 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14	Positive	1		0.1351351351	#6
6	DCMK-46 → SFTY-06 → DCMK-46	Positive	0	#6, #7	0.8648648649	#2
7	BHVR-16 → DCMK-20 → DCMK-07 → DCMK-53 → BHVR-16	Negative	0		−0.2972972973	#8
8	BHVR-06 → HLTH-03 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06	Negative	−1	#8–#10	−0.1351351351	#7
9	DCMK-46 → DCMK-35 → BHVR-21 → BHVR-17 → SFTY-06 → DCMK-46	Negative	−1		−0.5405405405	#10
10	COGB-54 → SFTY-06 → SFTY-07 → COGB-54	Negative	−1		−0.9189189189	#14
11	COGB-40 → COGB-29 → COGB-40	Negative	−2	#11–#14	−0.4054054054	#9
12	COGB-41 → COGB-40 → COGB-41	Negative	−2		−0.6486486486	#12
13	COGB-54 → BHVR-17 → SFTY-06 → SFTY-07 → COGB-54	Negative	−2		−1.108108108	#15
14	SFTY-06 → BHVR-17 → SFTY-06	Negative	−2		−1.297297297	#16
15	BHVR-23 → DCMK-55 → BHVR-02 → BHVR-23	Negative	−3	#15, #16	−0.5945945946	#11
16	COGB-41 → COGB-40 → COGB-29 → COGB-41	Negative	−3		−0.7297297297	#13

4.9. Critical Paths

Critical paths represent the most influential sequences of factor relationships within the network. Unlike loops, which indicate continuous feedback cycles, critical paths illustrate linear progressions of influence, mapping out the direct flow of the impact from one factor to another without returning to the starting point. Similarly to in the loop cycle analysis, critical paths were analysed based on two primary metrics: the unit weight and centrality weight. The highest positive unit weight recorded in the analysis was 11, meaning that the most impactful reinforcing paths consisted entirely of positive relationships, accumulating to this total weight. Consequently, 36 critical paths reached this maximum unit weight threshold. Similarly, the highest negative unit weight was −5, representing the strongest deteriorating influence of a sequence of factors. There were 33 critical paths that reached this negative unit weight. Additionally, the analysis identified the top 20 positive and negative critical paths based on their centrality weight, highlighting paths that involved highly interconnected and influential factors. All of these data are presented in Appendix C. These rankings provide valuable insights into which sequences of decisions and interactions have the greatest potential to shape safety performance in construction environments.

5. Discussion

The Discussion Section interprets the key findings from the analysis, highlighting the most influential factors and critical paths in shaping H&S outcomes in the construction sector.

5.1. Factors and Cognitive Biases

Identifying key factors in H&S decision-making is crucial for understanding how risk is assessed and how cognitive and behavioural tendencies influence workplace safety outcomes. For example, the complexity of construction projects makes it difficult to predict and manage safety risks effectively, as workers must process large amounts of information while navigating uncertain conditions [8,81]. A study by Gernand [21] found that as systems become more complex, individuals tend to overestimate reliability and underestimate the failure probability, increasing the likelihood of errors. Uncertainty is another factor that significantly affects safety-related decision-making, as it forces workers to rely on heuristic-based judgments [31], which may result in cognitive biases [82]. Workers experiencing high uncertainty may either become overly cautious, slowing down productivity [19,60], or rely on prior assumptions that may not apply to new situations [32]. Confirmation bias further exacerbates this issue, as workers tend to seek out information that aligns with their existing beliefs while ignoring contradictory evidence [30]. This is particularly problematic when workers believe that existing safety measures are sufficient [83], leading them to disregard new risk assessments or resist changes in safety protocols, a tendency reinforced by status quo bias, where individuals prefer maintaining familiar practices rather than adapting to evolving safety requirements [78].

This study analysed factors based on the degree of centrality, SLR frequency, and number of loops, identifying risk perception (SFTY-06), overconfidence bias (COG-41), optimism bias (COGB-40), and risk propensity (BHVR-17) as appearing in the top 10 in all three metric analyses and able to be deemed as the most dominant factors influencing H&S performance, as shown in Tables 11 and 12. The degree of centrality and number of loop values in both tables are identical because they represent the same analysis. Table 11 presents the key factors, while Table 12 focuses on cognitive biases.

Risk perception is crucial in preventing accidents and improving compliance with safety protocols. Workers with a heightened sense of risk perception are more likely to engage in proactive safety measures and identify hazards more accurately, thus improving workplace safety [84]. However, the misperception of risks, either by overestimating or underestimating them, can have serious consequences. If risks are underestimated, workers may engage in unsafe behaviours, increasing the likelihood of accidents [85]. Conversely, when risks are overestimated, limited resources may be spent on minor hazards, potentially leaving an insufficient capacity to address critical safety threats when they arise [21].

Table 11. Comparison of top factors between analyses.

Code	SLR	Rank	Code	Degree of Centrality	Rank	Code	Number of Loops	Rank
SFTY-06	29	1	SFTY-06	1.00000	1	SFTY-06	6	1
DCMK-07	21	2	DCMK-35	0.45946	2	DCMK-14	3	2
BHVR-23	21	2	DCMK-07	0.45946	2	COGB-40	3	2
DCMK-22	16	4	BHVR-23	0.43243	4	BHVR-22	3	2
DCMK-58	14	5	SFTY-05	0.40541	5	BHVR-17	3	2
DCMK-49	13	6	SFTY-13	0.35135	6	DCMK-19	3	2
DCMK-41	13	6	COGB-41	0.32432	7	DCMK-04	2	7
SFTY-12	12	8	COGB-40	0.32432	7	DCMK-46	2	7
DCMK-10	11	9	DCMK-12	0.29730	9	BHVR-16	2	7
DCMK-04	11	9	DCMK-10	0.29730	9	DCMK-22	2	7
BHVR-16	11	9	BHVR-17	0.29730	9	COGB-41	2	7
						COGB-29	2	7
						SFTY-07	2	7
						HLTH-02	2	7
						COGB-12	2	7
						DCMK-02	2	7
						COGB-54	2	7

Table 12. Comparison of top cognitive biases between analyses.

Code	SLR	Rank	Code	Degree of Centrality	Rank	Code	Number of Loops	Rank
COGB-60	10	1	SFTY-06	1.00000	1	SFTY-06	6	1
COGB-12	10	2	DCMK-35	0.45946	2	DCMK-14	3	2
COGB-41	9	2	DCMK-07	0.45946	2	COGB-40	3	2
COGB-40	8	4	BHVR-23	0.43243	4	BHVR-22	3	2
COGB-03	8	5	SFTY-05	0.40541	5	BHVR-17	3	2
COGB-34	7	6	SFTY-13	0.35135	6	DCMK-19	3	2
COGB-07	6	6	COGB-41	0.32432	7	DCMK-04	2	7
COGB-25	5	8	COGB-40	0.32432	7	DCMK-46	2	7
COGB-63	4	9	DCMK-12	0.29730	9	BHVR-16	2	7
COGB-54	4	9	DCMK-10	0.29730	9	DCMK-22	2	7
COGB-29	4	9	BHVR-17	0.29730	9	COGB-41	2	7
COGB-26	4	9				COGB-29	2	7
COGB-22	4	9				SFTY-07	2	7
COGB-08	4	9				HLTH-02	2	7
						COGB-12	2	7
						DCMK-02	2	7
						COGB-54	2	7

While risk perception is crucial, it can be undermined by overconfidence bias, which leads workers to overestimate their ability to assess and manage risks [33]. Overconfident workers may disregard safety guidelines, assuming their experience or intuition is sufficient to avoid hazards [8,15]. This false sense of security can result in noncompliance with safety measures, increasing the likelihood of incidents. Similarly, optimism bias influences how workers perceive potential risks by causing them to believe that negative events are less likely to occur to them compared to others [15].

Risk propensity further influences safety outcomes by determining individuals' willingness to take risks in workplace environments. Workers with higher risk propensity tend to be more risk-seeking when they perceive potential gains but become more risk-averse when facing possible losses [34]. This dual nature of risk-taking behaviour can significantly impact workplace safety, as individuals focusing on immediate rewards may bypass safety protocols, while those fearing negative consequences may hesitate in critical decision-making moments. Additionally, higher risk propensity is often associated with lower risk perception, making individuals less likely to recognise safety hazards [86]. Furthermore, Hasanzadeh et al. [25] found that risk propensity is not static but influenced by external factors such as productivity demands, stress levels, and the cognitive load, which can alter workers' decision-making processes.

5.2. Loops and Critical Paths

Cognitive biases influence factors that act individually or in conjunction. Hence, it is important to link them to the loops and critical paths they are associated with. To understand the cognitive biases influencing the decision factors affecting H&S in the construction industry, this study analysed feedback loops and critical paths reinforcing patterns of risk perception and safety behaviours.

5.2.1. Loops

Feedback loops can either amplify unsafe decision-making through self-reinforcing biases or strengthen protective behaviours that improve workplace safety. One of the factors involved is overconfidence bias, which causes individuals to overestimate their ability to control risks, reinforcing optimism bias [13], where workers perceive themselves as less likely to experience negative events [15]. This self-reinforcing loop can lead to risk compensation behaviours, where workers engage in more hazardous activities due to an inflated sense of safety [9,25,87].

Besides the self-reinforcing loops between overconfidence bias (COGB-41) and optimism bias (COGB-40), several other negative loops contribute to risk misjudgement and unsafe behaviours in construction environments. A prominent example is the cycle COGB-41 (overconfidence bias) → COGB-40 (optimism bias) → COGB-29 (illusion of control) → COGB-41, where overconfidence leads to an inflated sense of control over risks (COGB-29), reinforcing optimism bias (COGB-40), which in turn sustains overconfidence (COGB-41). This cycle causes workers to underestimate risks and assume they are less likely to experience negative events, increasing their likelihood of engaging in unsafe behaviours and neglecting critical safety measures.

Similarly, the loop BHVR-23 (uncertainty) → DCMK-55 (trade-offs) → BHVR-02 (ambivalence) → BHVR-23 illustrates how uncertainty can lead to decision hesitancy, where workers struggle with trade-offs (DCMK-55), leading to ambivalence (BHVR-02), ultimately delaying necessary safety actions. This hesitation increases the likelihood of exposure to hazardous conditions, as workers may fail to make timely risk assessments. Another key negative loop, SFTY-06 (risk perception) → BHVR-17 (risk propensity) → SFTY-06, demonstrates how poor risk perception can lead to greater willingness to take risks, reinforcing a cycle where high-risk behaviours become normalised, leading to increased accident probabilities. One of the most critical negative loops is COGB-54 (risk compensation) → BHVR-17 (risk propensity) → SFTY-06 (risk perception) → SFTY-07 (risk tolerance) → COGB-54, where risk compensation (COGB-54) paradoxically reduces workers' perceived risk, leading them to engage in more hazardous activities under the false assumption that safety interventions eliminate danger. This loop demonstrates how well-intended safety measures can inadvertently encourage unsafe behaviours rather than reinforcing caution.

On the other hand, positive reinforcing loops demonstrate how structured decision-making, cognitive adaptability, and risk awareness create safer work environments. One such loop, BHVR-16 (risk aversion) → COGB-60 (status quo bias) → BHVR-16, highlights how a cautious approach to risk reinforces adherence to existing safety protocols. While status quo bias (COGB-60) may sometimes hinder adaptability, it stabilises risk-averse behaviour in this loop, ensuring that safety measures remain consistently followed and preventing reckless decision-making. Another reinforcing loop, DCMK-14 (Domain Expertise) → DCMK-22 (Information Availability) → BHVR-22 (trust) → DCMK-19 (Group/Team Dynamics) → DCMK-14, emphasises how expertise fosters information-sharing (DCMK-22), building trust (BHVR-22) and strengthening collaboration (DCMK-19). This cycle ensures that critical safety information circulates effectively within teams, reinforcing expertise (DCMK-14) and improving overall hazard awareness.

5.2.2. Critical Paths

Understanding critical paths between key factors influencing decision-making is essential for identifying the most influential sequences of factor relationships that shape safety outcomes. By analysing these paths, this study highlights the most impactful sequences affecting H&S performance, positively or negatively.

The analysis identified 64,799 critical paths, of which 63,798 directly impacted H&S performance, demonstrating the extensive interplay of decision factors in construction safety. These critical paths were evaluated using unit and centrality weights to quantify their influence on H&S performance. The unit weight measures the overall impact of a path by summing the assigned values of each relationship, with +1 assigned for a positive relation and −1 for a negative relation. Meanwhile, the centrality weight identifies structurally important paths by summing the centrality values of all factors within a sequence. A higher centrality weight indicates frequently recurring factors that shape multiple decision pathways, making them key influencers of H&S performance.

The five identified negative critical paths highlight how decision-making heuristics, uncertainty, complexity, cognitive biases, and risk propensity lead to ineffective safety decisions that negatively impact H&S performance (STCK-01). These paths share similar structures, with minor variations in factor sequences, but all demonstrate how risk misjudgement, limited information, and the cognitive workload contribute to safety failures in construction environments. The top five negative critical paths are as follows:

- BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01.
- BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01.
- BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01.
- BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01.
- BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 →

DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01.

Across all five negative critical paths, the chains start with recurring factors such as BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21, which lead to a negative safety outcome or increase the risk. Fast and frugal heuristics (BHVR-11) positively influence decision-making frameworks (DCMK-12) by allowing for quick responses in dynamic environments. However, reliance on structured decision tools (DCMK-12) negatively influences uncertainty (BHVR-23), as rigid frameworks may limit adaptability to evolving risks. This uncertainty disrupts project scheduling (DCMK-40), causing inefficiencies and technical challenges (DCMK-53), which lead to risk-averse behaviour (BHVR-16). While risk aversion encourages cautious decision-making (DCMK-20), it also increases complexity (DCMK-07), as simplified decision processes fail to account for emerging hazards. This growing complexity results in incomplete or limited knowledge (DCMK-21), weakening safety assessments. The top negative critical path demonstrates how overestimation (BHVR-15) leads to resource mismanagement (DCMK-10 and DCMK-46), reducing the effectiveness of risk perception (SFTY-06). When workers and managers overestimate their ability to manage risks, safety investments may be misallocated, leading to higher exposure to hazards. This further increases risk-taking behaviours (BHVR-17), thus resulting in ineffective safety decisions (OTHR-03), ultimately harming H&S performance (STCK-01).

The five positive critical paths illustrate how work experience, structured decision-making, cognitive adaptability, and situational awareness enhance H&S performance (STCK-01). These paths share similar structures, with minor variations in factor sequences. However, they all demonstrate how cognitive processing, risk evaluation, and safety behaviours collectively contribute to proactive safety management in construction environments.

The top five positive critical paths are as follows:

- DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-05 → OTHR-02 → STCK-01.
- DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01.
- DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-05 → OTHR-02 → STCK-01.
- DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01.
- DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01.

Across all five positive critical paths, the chains have recurring factors: heuristics (DCMK-20) → complexity (DCMK-07) → overconfidence bias (COGB-41) → optimism bias (COGB-40) → cognitive workload (DCMK-04) → performance demands (HLTH-02) → cognitive demand (DCMK-02) → cognitive overload (BHVR-06) → physical fatigue (HLTH-03) → distractions (DCMK-13) → risk assessment (SFTY-05)/risk perception (SFTY-06)/risk tolerance (SFTY-07). This sequence highlights how complexity, cognitive biases, and workload pressures initially introduce challenges that could negatively impact safety performance if left unchecked. The presence of overconfidence bias (COGB-41) and optimism bias (COGB-40) increases the likelihood of misjudging risks, while the cognitive workload (DCMK-04) and performance demands (HLTH-02) create additional pressure on workers to make quick decisions (DCMK-02). As the workload intensifies, cognitive overload (BHVR-06) leads to physical and mental fatigue (HLTH-03) and increased distractions (DCMK-13), reducing situational awareness. However, what makes these paths distinctly positive is the introduction of risk assessment (SFTY-05), risk perception (SFTY-06), or risk tolerance (SFTY-07) at the end of the sequence. These safety mechanisms act as corrective factors, ensuring that initial cognitive challenges and biases do not lead to ineffective decision-making but reinforce structured risk evaluations.

The positive critical paths demonstrate how experience, structured decision-making, and proactive safety evaluations create resilience against cognitive biases and workload strain. By incorporating risk assessment and perception into the decision-making process, these paths ensure that safety measures are upheld despite operational challenges. Through effective training, workload management, and structured risk evaluation frameworks, organisations can leverage these positive paths to reinforce proactive safety cultures, minimise workplace hazards, and ensure sustainable improvements in H&S performance.

6. Conclusions

This study explored the impact of cognitive biases and decision-making processes on H&S performance in construction environments. Through a SLR and degree of centrality analysis, it identified key determinants that significantly influence risk evaluation, safety compliance, and workplace decision-making. Among the factors and cognitive biases identified in this study, risk perception, risk propensity, overconfidence bias, and optimism bias emerged as the most influential factors affecting safety outcomes.

The findings also highlight the presence of feedback loops, which can either strengthen structured safety mechanisms or perpetuate biases that contribute to unsafe behaviours. Additionally, critical paths between the factors were analysed, illustrating how cognitive biases, complexity, and workload demands shape risk perception and responsiveness to workplace hazards.

The top three loops that involve cognitive biases are as follows:

- Trust (DCMK-14) → Group/Team Dynamics (DCMK-22) → Domain Expertise (BHVR-22) → Information Availability (DCMK-19) → trust (DCMK-14).
- Risk aversion (BHVR-16) → status quo bias (COGB-60) → risk aversion (BHVR-16).
- Overconfidence bias (COGB-41) → optimism bias (COGB-40) → illusion of control (COGB-29) → overconfidence bias (COGB-41).

Similarly, the top two most influential critical paths are as follows:

- Heuristics (DCMK-20) → complexity (DCMK-07) → overconfidence bias (COGB-41) → optimism bias (COGB-40) → cognitive workload (DCMK-04) → performance demands (HLTH-02) → cognitive demand (DCMK-02) → cognitive overload (BHVR-06) → physical fatigue (HLTH-03) → distractions (DCMK-13).
- Fast and frugal heuristics (BHVR-11) → Decision-Making Method/Framework (DCMK-12) → uncertainty (BHVR-23) → project scheduling (DCMK-40) → technical challenges (DCMK-53) → risk aversion (BHVR-16) → heuristics (DCMK-20) → complexity (DCMK-07) → Incomplete/Limited Information (DCMK-21).

6.1. Research Limitations

This study, while comprehensive, has several limitations. The analysis relied on secondary data from the published literature, which may have introduced selection biases and limits generalizability to specific construction contexts. Additionally, while the study identifies key reinforcing loops and their impact on decision-making, empirical validation through industry case studies or real-world observations is required to quantify their direct effects. Future research should aim to empirically test these reinforcing loops using field data, conduct cross-cultural analyses to identify contextual differences in risk perception, and explore practical strategies for breaking negative feedback cycles in construction safety management. Lastly, the inclusion of only English-language sources and reliance on specific databases may also have resulted in the exclusion of relevant findings from regional studies or non-indexed publications. Furthermore, the search predominately focused on journal papers, with a limited inclusion of conference proceedings, which may have excluded emerging research or preliminary findings that could provide additional insights. These limitations are acknowledged.

6.2. Practical and Theoretical Implications

By identifying how cognitive biases influence safety-related decision-making and reinforcing safety mechanisms that counteract risk-taking behaviours, this study provides valuable insights into improving safety management strategies in construction. The findings suggest that understanding the interaction between cognitive biases and H&S performance can help construction professionals develop tailored interventions, ensuring that risk perception remains aligned with actual hazards rather than cognitive distortions. Future studies could expand on this research by quantifying the effectiveness of cognitive bias mitigation strategies, developing industry-specific safety protocols based on the identified reinforcing loops, and integrating behavioural psychology insights into safety training programmes.

Understanding the complex interplay of cognitive biases, safety protocols, and decision-making structures is critical for fostering a proactive safety culture. By leveraging positive reinforcing loops, mitigating negative ones, and strengthening critical risk perception pathways, construction professionals and policymakers can develop evidence-based interventions that enhance safety compliance, reduce workplace hazards, and improve the overall construction site safety performance.

Author Contributions: Conceptualization, M.B.P. and P.J; methodology, M.B.P.; software, P.J.; validation, M.B.P., P.J. and F.E.R.; formal analysis, P.J.; investigation, P.J.; resources, M.B.P.; data curation, P.J.; writing—original draft preparation, P.J.; writing—review and editing, M.B.P. and F.E.R.; visualization, P.J.; supervision, M.B.P.; project administration, M.B.P.; funding acquisition, M.B.P. All authors have read and agreed to the published version of the manuscript.

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Abbreviations

The following abbreviations are used in this manuscript:

CLD	Causal loop diagram
H&S	Health and safety
SLR	Systematic literature review

Appendix A

Table A1. Author–behavioural, health, and safety factor matrix.

AN	Author	Country	BHVR-01	BHVR-02	BHVR-03	BHVR-04	BHVR-05	BHVR-06	BHVR-07	BHVR-08	BHVR-09	BHVR-10	BHVR-11	BHVR-12	BHVR-13	BHVR-14	BHVR-15	BHVR-16	BHVR-17	BHVR-18	BHVR-19	BHVR-20	BHVR-21	BHVR-22	BHVR-23	BHVR-24	HLTH-01	HLTH-02	HLTH-03	HLTH-04	SFTY-01	SFTY-02	SFTY-03	SFTY-04	SFTY-05	SFTY-06	SFTY-07	SFTY-08	SFTY-09	SFTY-10	SFTY-11	SFTY-12	SFTY-13
1	Mostofi et al. [19]	Turkey																							✓							✓							✓				
2	Gernand [21]	United States															✓	✓																	✓	✓							
3	Sörqvist et al. [35]	Sweden																																		✓							
4	Alzayed et al. [36]	Kuwait	✓								✓																									✓							
5	Brown et al. [37]	United States	✓															✓							✓																		
6	Protte et al. [33]	Australia															✓	✓							✓											✓							
7	Ball et al. [32]	New Zealand			✓																✓			✓								✓	✓		✓	✓	✓	✓					
8	JordÃO et al. [13]	Portugal			✓												✓	✓						✓												✓							
9	Shealy et al. [38]	United States					✓								✓									✓	✓											✓							
10	Marois et al. [39]	Canada						✓	✓					✓									✓	✓	✓			✓	✓	✓													
11	Zhou [30]	United States																							✓	✓																	
12	Kinsey et al. [31]	China																							✓										✓								
13	Du et al. [34]	United States						✓									✓	✓	✓	✓					✓											✓	✓						
14	McWhirter et al. [40]	United States			✓	✓	✓											✓			✓				✓		✓			✓						✓							
15	Kavvada et al. [88]	United States	✓													✓									✓								✓			✓	✓						
16	Schöttle et al. [89]	Germany																												✓													
17	Pooladvand et al. [9]	United States						✓									✓		✓				✓		✓			✓		✓	✓					✓		✓		✓		✓	✓
18	Kotluk et al. [90]	Switzerland																																									
19	ElSayed et al. [82]	United States																																									
20	Nelius et al. [14]	Germany								✓																																	
21	Witherell et al. [91]	United States										✓										✓		✓				✓															
22	Love et al. [92]	Australia			✓								✓								✓				✓										✓	✓							

Table A1. *Cont.*

AN	Author	Country	BHVR-01	BHVR-02	BHVR-03	BHVR-04	BHVR-05	BHVR-06	BHVR-07	BHVR-08	BHVR-09	BHVR-10	BHVR-11	BHVR-12	BHVR-13	BHVR-14	BHVR-15	BHVR-16	BHVR-17	BHVR-18	BHVR-19	BHVR-20	BHVR-21	BHVR-22	BHVR-23	BHVR-24	HLTH-01	HLTH-02	HLTH-03	HLTH-04	SFTY-01	SFTY-02	SFTY-03	SFTY-04	SFTY-05	SFTY-06	SFTY-07	SFTY-08	SFTY-09	SFTY-10	SFTY-11	SFTY-12	SFTY-13
23	Delgado et al. [93]	United States			✓	✓		✓																				✓		✓													
24	Bellamy et al. [12]	The Netherlands																							✓					✓	✓				✓	✓						✓	
25	Zheng et al. [94]	United States								✓												✓		✓	✓										✓								
26	Bolognani et al. [7]	Italy																							✓											✓							
27	Farooq et al. [60]	Pakistan															✓	✓	✓						✓			✓							✓	✓							
28	Ibrahim et al. [84]	United States						✓																	✓				✓		✓				✓	✓		✓	✓			✓	✓
29	Hasanzadeh et al. [83]	United States																																		✓	✓	✓		✓	✓	✓	✓
30	Chen et al. [85]	Hong Kong						✓																							✓					✓		✓		✓	✓	✓	✓
31	Pooladvand et al. [26]	United States						✓	✓										✓				✓					✓	✓	✓						✓	✓			✓			✓
32	Hu et al. [95]	United States																✓									✓									✓	✓						
33	Hasanzadeh et al. [25]	United States																	✓				✓		✓			✓	✓	✓	✓					✓	✓			✓	✓	✓	✓
34	Wang et al. [86]	China							✓										✓																	✓	✓					✓	✓
35	Shi et al. [81]	China																	✓									✓			✓			✓		✓		✓	✓			✓	
36	Xu et al. [96]	China	✓																					✓																			
37	Nelius et al. [97]	Germany								✓							✓								✓																		
38	Grill et al. [4]	Sweden									✓																					✓						✓	✓				
39	Ma et al. [15]	China		✓	✓													✓							✓				✓						✓	✓	✓	✓	✓		✓	✓	✓
40	Aroke et al. [10]	United States					✓	✓																												✓						✓	
41	Baybutt [41]	United States																			✓									✓													
42	Li et al. [8]	China																													✓					✓			✓			✓	✓
43	Gerassis et al. [98]	Spain																✓																	✓	✓				✓	✓	✓	
44	Lappalainen et al. [99]	Finland																													✓					✓							
45	Fellows et al. [100]	United Kingdom	✓		✓													✓			✓				✓			✓								✓							

Table A2. Author–decision-making factor matrix.

AN	DCMK-01	DCMK-02	DCMK-03	DCMK-04	DCMK-05	DCMK-06	DCMK-07	DCMK-08	DCMK-09	DCMK-10	DCMK-11	DCMK-12	DCMK-13	DCMK-14	DCMK-15	DCMK-16	DCMK-17	DCMK-18	DCMK-19	DCMK-20	DCMK-21	DCMK-22	DCMK-23	DCMK-24	DCMK-25	DCMK-26	DCMK-27	DCMK-28	DCMK-29	DCMK-30
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AN	DCMK-31	DCMK-32	DCMK-33	DCMK-34	DCMK-35	DCMK-36	DCMK-37	DCMK-38	DCMK-39	DCMK-40	DCMK-41	DCMK-42	DCMK-43	DCMK-44	DCMK-45	DCMK-46	DCMK-47	DCMK-48	DCMK-49	DCMK-50	DCMK-51	DCMK-52	DCMK-53	DCMK-54	DCMK-55	DCMK-56	DCMK-57	DCMK-58	DCMK-59
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AN	DCMK-01	DCMK-02	DCMK-03	DCMK-04	DCMK-05	DCMK-06	DCMK-07	DCMK-08	DCMK-09	DCMK-10	DCMK-11	DCMK-12	DCMK-13	DCMK-14	DCMK-15	DCMK-16	DCMK-17	DCMK-18	DCMK-19	DCMK-20	DCMK-21	DCMK-22	DCMK-23	DCMK-24	DCMK-25	DCMK-26	DCMK-27	DCMK-28	DCMK-29	DCMK-30	DCMK-31	DCMK-32	DCMK-33	DCMK-34	DCMK-35	DCMK-36	DCMK-37	DCMK-38	DCMK-39	DCMK-40	DCMK-41	DCMK-42	DCMK-43	DCMK-44	DCMK-45	DCMK-46	DCMK-47	DCMK-48	DCMK-49	DCMK-50	DCMK-51	DCMK-52	DCMK-53	DCMK-54	DCMK-55	DCMK-56	DCMK-57	DCMK-58	DCMK-59
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Table A3. Author–cognitive bias matrix.

AN	COGB-01	COGB-02	COGB-03	COGB-04	COGB-05	COGB-06	COGB-07	COGB-08	COGB-09	COGB-10	COGB-11	COGB-12	COGB-13	COGB-14	COGB-15	COGB-16	COGB-17	COGB-18	COGB-19	COGB-20	COGB-21	COGB-22	COGB-23	COGB-24	COGB-25	COGB-26	COGB-27	COGB-28	COGB-29	COGB-30	COGB-31	COGB-32	COGB-33	COGB-34	COGB-35	COGB-36	COGB-37	COGB-38	COGB-39	COGB-40	COGB-41	COGB-42	COGB-43	COGB-44	COGB-45	COGB-46	COGB-47	COGB-48	COGB-49	COGB-50	COGB-51	COGB-52	COGB-53	COGB-54	COGB-55	COGB-56	COGB-57	COGB-58	COGB-59	COGB-60	COGB-61	COGB-62	COGB-63	COGB-64
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Table A3. *Cont.*

AN	COGB-01	COGB-02	COGB-03	COGB-04	COGB-05	COGB-06	COGB-07	COGB-08	COGB-09	COGB-10	COGB-11	COGB-12	COGB-13	COGB-14	COGB-15	COGB-16	COGB-17	COGB-18	COGB-19	COGB-20	COGB-21	COGB-22	COGB-23	COGB-24	COGB-25	COGB-26	COGB-27	COGB-28	COGB-29	COGB-30	COGB-31	COGB-32	COGB-33	COGB-34	COGB-35	COGB-36	COGB-37	COGB-38	COGB-39	COGB-40	COGB-41	COGB-42	COGB-43	COGB-44	COGB-45	COGB-46	COGB-47	COGB-48	COGB-49	COGB-50	COGB-51	COGB-52	COGB-53	COGB-54	COGB-55	COGB-56	COGB-57	COGB-58	COGB-59	COGB-60	COGB-61	COGB-62	COGB-63	COGB-64
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Appendix B

Table A4. Interrelation matrix (gree indicates positive; Red indicatesnegative).

Factors	BHVR-02	BHVR-03	BHVR-06	BHVR-08	BHVR-09	BHVR-10	BHVR-14	BHVR-15	BHVR-16	BHVR-17	BHVR-18	BHVR-19	BHVR-20	BHVR-21	BHVR-22	BHVR-23
BHVR-01															[36]	[45]
BHVR-02																[39]
BHVR-04			[23]													
BHVR-06																
BHVR-07																
BHVR-09																
BHVR-11																
BHVR-13																
BHVR-15																
BHVR-16								[27]								
BHVR-17																
BHVR-20																
BHVR-21										[17]						
BHVR-22																
BHVR-23							[15]			[33]		[14]				
BHVR-24																
COGB-02																
COGB-03								[2]								
COGB-06																
COGB-12				[20] [25]												
COGB-13																
COGB-14																
COGB-18																
COGB-22																
COGB-25																
COGB-28																
COGB-29																
COGB-34																
COGB-35																
COGB-37																
COGB-39																

Factors	COGB-03	COGB-05	COGB-08	COGB-12	COGB-25	COGB-26	COGB-29	COGB-34	COGB-35	COGB-40	COGB-41	COGB-42	COGB-44	COGB-45	COGB-50	COGB-51	COGB-52	COGB-54	COGB-55	COGB-60	COGB-63
BHVR-01																					
BHVR-02																					
BHVR-04																					
BHVR-06															[13]			[31]			
BHVR-07																					
BHVR-09																					
BHVR-11																					
BHVR-13																					
BHVR-15																[13]		[17]			
BHVR-16										[39]										[14]	
BHVR-17																					
BHVR-20																					
BHVR-21																					
BHVR-22																					
BHVR-23								[27]									[26]				[11]
BHVR-24																					
COGB-02																					
COGB-03																					
COGB-06											[10]										
COGB-12																					
COGB-13																					
COGB-14																					
COGB-18																			[11]		
COGB-22	[11]																				
COGB-25																					
COGB-28											[6]										
COGB-29										[8]	[6]										
COGB-34																					
COGB-35																					
COGB-37																					
COGB-39																					

Factors	DCMK-02	DCMK-03	DCMK-04	DCMK-05	DCMK-07	DCMK-08	DCMK-10	DCMK-11	DCMK-12	DCMK-13	DCMK-14	DCMK-15	DCMK-18	DCMK-19	DCMK-20	DCMK-21	DCMK-22	DCMK-23	DCMK-25	DCMK-29	DCMK-30	DCMK-34	DCMK-35	DCMK-36	DCMK-38	DCMK-40	DCMK-41	DCMK-42	DCMK-43	DCMK-44	DCMK-45	DCMK-46	DCMK-47	DCMK-48	DCMK-49	DCMK-50	DCMK-52	DCMK-53	DCMK-55	DCMK-57
BHVR-01																																								
BHVR-02																																								
BHVR-04																																								
BHVR-06																							[31]																	
BHVR-07																																								
BHVR-09																												[4]						[4]						
BHVR-11									[22]																															
BHVR-13			[9]																																					
BHVR-15							[2]																																	
BHVR-16															[22]																									
BHVR-17																																								
BHVR-20								[21]															[21]																	
BHVR-21																																								
BHVR-22														[21]																										
BHVR-23							[27]								[6] [13]								[1]			[27]									[28]				[17]	
BHVR-24																																					[11]			
COGB-02					[5]																																			
COGB-03																																								
COGB-06																																			[10]					
COGB-12								[11]									[11] [37]	[37]													[11]									[37]
COGB-13																																								
COGB-14																[41]																								
COGB-18																																								
COGB-22																											[11]													
COGB-25								[21]																																
COGB-28																																								
COGB-29																																								
COGB-34																																								
COGB-35																																								
COGB-37																				[11]																				
COGB-39																																								

Factors	HLTH-02	HLTH-03	SFTY-04	SFTY-05	SFTY-06	SFTY-07	SFTY-08	SFTY-09	SFTY-13
BHVR-01									
BHVR-02									
BHVR-04									
BHVR-06		[28]			[31]				[17] [30] [31]
BHVR-07					[34]				
BHVR-09							[38]	[38]	
BHVR-11									
BHVR-13									
BHVR-15									
BHVR-16				[12]	[2]				
BHVR-17					[34]				[34]
BHVR-20									
BHVR-21									
BHVR-22				[7]					
BHVR-23									
BHVR-24									
COGB-02									
COGB-03									
COGB-06									
COGB-12									
COGB-13					[7]				
COGB-14									
COGB-18									
COGB-22									
COGB-25									
COGB-28									
COGB-29									
COGB-34					[15]				
COGB-35					[7]				
COGB-37									
COGB-39				[12]					

Table A4. *Cont.*

Factors	BHVR-02	BHVR-03	BHVR-06	BHVR-08	BHVR-09	BHVR-10	BHVR-14	BHVR-15	BHVR-16	BHVR-17	BHVR-18	BHVR-19	BHVR-20	BHVR-21	BHVR-22	BHVR-23	COGB-03	COGB-05	COGB-08	COGB-12	COGB-25	COGB-26	COGB-29	COGB-34	COGB-35	COGB-40	COGB-41	COGB-42	COGB-44
COGB-40																							[27]				[39]		[8]
COGB-41								[6]																		[8]			
COGB-42																													
COGB-43																													
COGB-44																													
COGB-46																													
COGB-49																													
COGB-50																													
COGB-54										[31]																			
COGB-55																													
COGB-57																											[6]		
COGB-60									[32]															[9]				[21]	
DCMK-01															[21]														
DCMK-02			[17]											[17]															
DCMK-03															[36]														
DCMK-04										[17]																			
DCMK-05															[21]													[21]	
DCMK-06																													
DCMK-07		[14]						[2]																	[7]		[6]		
DCMK-10																													
DCMK-11																													
DCMK-12				[25]									[25]			[25]			[25]	[25]		[25]						[25]	
DCMK-13																													
DCMK-14																		[41]		[20]									
DCMK-15																													
DCMK-16										[35]																			
DCMK-17						[21]							[21]								[21]						[6]	[21]	
DCMK-18																													
DCMK-19																													
DCMK-20																													
DCMK-21		[14]						[2]			[13]																		
DCMK-22															[36]														
DCMK-23																													
DCMK-24																													
DCMK-26									[43]																				
DCMK-27																												[21]	

Factors	COGB-45	COGB-50	COGB-51	COGB-52	COGB-54	COGB-55	COGB-60	COGB-63	DCMK-02	DCMK-03	DCMK-04	DCMK-05	DCMK-07	DCMK-08	DCMK-10	DCMK-11	DCMK-12	DCMK-13	DCMK-14	DCMK-15	DCMK-18	DCMK-19	DCMK-20	DCMK-21	DCMK-22	DCMK-23	DCMK-25	DCMK-29
COGB-40											[39]				[13] [14]												[8]	
COGB-41																											[8]	
COGB-42																												
COGB-43																												[11]
COGB-44															[14]													
COGB-46																												
COGB-49																												
COGB-50																												
COGB-54																												
COGB-55																[11]												
COGB-57																												
COGB-60															[23]													
DCMK-01												[21]																
DCMK-02										[17] [33]																		
DCMK-03																												
DCMK-04	[3]																											
DCMK-05										[14]						[21]									[14]			
DCMK-06																												
DCMK-07			[27]												[1]									[13]				
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DCMK-11															[25]													
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DCMK-19																			[21]									
DCMK-20									[41]				[19]			[19]												
DCMK-21			[13]								[1]																	
DCMK-22																												
DCMK-23											[13]																	
DCMK-24																												[30]
DCMK-26															[13]													
DCMK-27																												

Factors	DCMK-30	DCMK-34	DCMK-35	DCMK-36	DCMK-38	DCMK-40	DCMK-41	DCMK-42	DCMK-43	DCMK-44	DCMK-45	DCMK-46	DCMK-47	DCMK-48	DCMK-49	DCMK-50	DCMK-52	DCMK-53	DCMK-55	DCMK-57	HLTH-02	HLTH-03	SFTY-04	SFTY-05	SFTY-06	SFTY-07	SFTY-08	SFTY-09	SFTY-13
COGB-40																								[12]	[7] [13] [39]				[39]
COGB-41																									[6] [8] [9]				
COGB-42														[4]															
COGB-43																													
COGB-44																													
COGB-46																	[11]												
COGB-49																									[7]				
COGB-50																									[3]				
COGB-54																									[31]				[17] [29]
COGB-55											[11]																		
COGB-57																													
COGB-60											[11] [32]																		
DCMK-01																													
DCMK-02																									[17]				
DCMK-03																				[40]									
DCMK-04																					[10]								
DCMK-05																									[7]				
DCMK-06					[14]																								
DCMK-07			[1]															[13]				[31]	[35]	[7] [27]	[2]				
DCMK-10												[43]													[32]				
DCMK-11																													
DCMK-12																								[25]					
DCMK-13															[28] [33]									[28]	[28]				
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DCMK-20																								[22]					[30]
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DCMK-24															[7]														
DCMK-26																													[33]
DCMK-27																													

Table A4. *Cont.*

Factors	BHVR-02	BHVR-03	BHVR-06	BHVR-08	BHVR-09	BHVR-10	BHVR-14	BHVR-15	BHVR-16	BHVR-17	BHVR-18	BHVR-19	BHVR-20	BHVR-21	BHVR-22	BHVR-23	COGB-03	COGB-05	COGB-08	COGB-12	COGB-25	COGB-26	COGB-29	COGB-34	COGB-35	COGB-40	COGB-41	COGB-42	COGB-44	COGB-45	COGB-50	COGB-51	COGB-52	COGB-54	COGB-55	COGB-60	COGB-63	DCMK-02	DCMK-03	DCMK-04	DCMK-05	DCMK-07	DCMK-08	DCMK-10	DCMK-11	DCMK-12	DCMK-13	DCMK-14	DCMK-15	DCMK-18	DCMK-19	DCMK-20	DCMK-21	DCMK-22	DCMK-23	DCMK-25	DCMK-29	DCMK-30	DCMK-34	DCMK-35	DCMK-36	DCMK-38	DCMK-40	DCMK-41	DCMK-42	DCMK-43	DCMK-44	DCMK-45	DCMK-46	DCMK-47	DCMK-48	DCMK-49	DCMK-50	DCMK-52	DCMK-53	DCMK-55	DCMK-57	HLTH-02	HLTH-03	SFTY-04	SFTY-05	SFTY-06	SFTY-07	SFTY-08	SFTY-09	SFTY-13
DCMK-28																																									[38]																																																
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DCMK-51		[23]																																		[14]																											[13]					[9]																		
DCMK-52																														[3]	[3]																																																									
DCMK-53									[43]																																																																									[35]						
DCMK-55	[39]	[14]										[14]																																																																										
DCMK-56					[38]																																																							[38]						[16]																[44]		[38]	[38]	
DCMK-58								[2]		[35]					[36]												[6]									[32]																																				[34] [40]	[32]								[2]	[40]				
DCMK-59																												[21]						[31]																										[1]																										
HLTH-02						[21]				[17] [27] [35]		[45]		[31]																								[23]																						[33]											[33]														[31]
HLTH-03																																								[28]							[33]													[33]											[28] [31]									[28]	[28]				[28] [31]
HLTH-04												[14]		[17] [31]																				[31]					[17]			[31]																		[31]											[31]										[17]				[31]
SFTY-01																																										[24]																																															
SFTY-02																																																											[1]																									[38]	
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SFTY-10														[33]																				[29] [33]																										[33]																						[17] [29] [31] [33]	[29]	[30]		[29] [31]
SFTY-11																																																																																					[29]		[39]
SFTY-12																																																																																			[28] [35]		[17] [29] [30] [39]		[17]

The numbers in the cells relate to AN in Appendix A, Table A1.

Appendix C

Table A5. Top 36 positive-unit-weight critical paths.

Path	Cycle Length	Unit Weight
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	18	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	20	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	20	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	18	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	20	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	20	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	11
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-05 → OTHR-02 → STCK-01	18	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	20	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	20	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-22 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-05 → OTHR-02 → STCK-01	20	11

Table A5. *Cont.*

Path	Cycle Length	Unit Weight
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	20	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	20	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	22	11
DCMK-56 → DCMK-43 → DCMK-05 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-05 → OTHR-02 → STCK-01	20	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	18	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	20	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	20	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → OTHR-02 → STCK-01	18	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	20	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	20	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	11
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-05 → OTHR-02 → STCK-01	18	11

Table A6. Top 33 negative-unit-weight critical paths.

Path	Cycle Length	Unit Weight
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → STCK-01	10	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	14	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	14	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	14	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	14	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	20	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	20	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	22	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	22	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	14	−5
DCMK-51 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	14	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → STCK-01	6	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	10	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	10	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	10	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	10	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	16	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	18	−5
COGB-02 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	18	−5
COGB-02 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	10	−5
COGB-02 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	10	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → STCK-01	12	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	16	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−5

Table A6. *Cont.*

Path	Cycle Length	Unit Weight
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	16	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	22	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-23 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	22	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	24	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	24	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−5
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	16	−5

Table A7. Top 20 positive-centrality-weight critical paths.

Path	Cycle Length	Centrality Weight	Rank Centrality Weight
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	4.243243243	#1
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	4.135135135	#2
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	4.108108108	#3
SFTY-03 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	4.027027027	#4, #5
BHVR-01 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	4.027027027	
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	4	6
HLTH-04 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	17	3.972972973	7
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → STCK-01	19	3.945945946	#8, #9
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	20	3.945945946	
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	3.918918919	10

Table A7. *Cont.*

Path	Cycle Length	Centrality Weight	Rank Centrality Weight
SFTY-03 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	3.891891892	#11, #12
BHVR-01 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	3.891891892	
DCMK-51 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	20	3.891891892	13
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → SFTY-13 → STCK-01	20	3.891891892	14
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	3.864864865	#15, #16
DCMK-26 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	3.864864865	
HLTH-04 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → DCMK-49 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	17	3.837837838	#17–#20
DCMK-58 → COGB-60 → BHVR-16 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-06 → SFTY-07 → COGB-54 → BHVR-17 → OTHR-03 → STCK-01	19	3.837837838	
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → STCK-01	19	3.837837838	
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-20 → DCMK-07 → COGB-41 → COGB-40 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → HLTH-03 → DCMK-13 → SFTY-05 → SFTY-06 → SFTY-07 → COGB-54 → OTHR-01 → OTHR-03 → STCK-01	20	3.837837838	

Table A8. Top 20 negative-centrality-weight critical paths.

Path	Cycle Length	Centrality Weight	Rank Centrality Weight
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−2.864864865	#1
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−2.675675676	#2, #3
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	24	−2.675675676	

Table A8. *Cont.*

Path	Cycle Length	Centrality Weight	Rank Centrality Weight
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−2.621621622	#4
SFTY-03 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	15	−2.540540541	#5, #6
BHVR-01 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	15	−2.540540541	
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → OTHR-03 → STCK-01	16	−2.513513514	#7, #8
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → BHVR-06 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	17	−2.513513514	
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	13	−2.459459459	#9, #10
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → COGB-54 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	15	−2.459459459	
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → BHVR-17 → SFTY-06 → DCMK-46 → BHVR-19 → OTHR-03 → STCK-01	17	−2.432432432	#11–#13
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	13	−2.432432432	
DCMK-55 → BHVR-02 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	16	−2.432432432	
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → BHVR-15 → DCMK-10 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	15	−2.405405405	#14
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → DCMK-46 → BHVR-19 → OTHR-03 → STCK-01	17	−2.351351351	#15–#20
SFTY-03 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	15	−2.351351351	
SFTY-03 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	23	−2.351351351	
BHVR-01 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-49 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	15	−2.351351351	
BHVR-01 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-21 → DCMK-04 → HLTH-02 → DCMK-02 → DCMK-03 → BHVR-22 → DCMK-19 → DCMK-14 → COGB-12 → DCMK-11 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	23	−2.351351351	
BHVR-11 → DCMK-12 → BHVR-23 → DCMK-40 → DCMK-53 → BHVR-16 → DCMK-20 → DCMK-07 → DCMK-10 → DCMK-46 → SFTY-06 → BHVR-17 → SFTY-13 → STCK-01	14	−2.351351351	

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