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Enhancing Fire Resilience in High-Tech Electronic Plants for Sustainable Development: Combining System Composition with Organizational Management

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Abstract: In the realm of sustainable advancements, high-tech electronics plants have evolved concomitantly with the innovations in environmentally conscious high-tech manufacturing. Nonetheless, the potential for fires in these establishments presents a profound challenge, jeopardizing both human resources and assets, while also bearing ecological implications. However, difficulty exists in understanding the system composition and fire protection features specific to the production environment. Meanwhile, sustainable development-oriented organizational countermeasures for fire resilience are rarely explored in the operations environment. Through a literature review, hypotheses development, an industrial survey, and PLS-SEM analysis using data from 84 questionnaires, this research aims to fill this gap by analyzing the system composition of high-tech electronics plants and its influence on fire resilience, emphasizing the organizational perspective. This study delves into the fire resilience of high-tech electronics plants, drawing particular attention to the imperative of fire prevention, detection, and mitigation measures. The discourse is framed within the paradigm of design-for-sustainability thinking, underscoring the integration of sustainable practices in enhancing fire resilience. By examining the interplay between various functional and organizational system composition elements, three key aspects are extracted to enhance fire resilience: (1) fire protection design measure improvement, (2) sustainable and fireproof construction facility, and (3) organizational management support. The findings contribute to a better understanding of the complex nature of high-tech electronics plants, and provide actionable insights for enhancing both fire resilience and sustainable practices in these establishments.

Keywords: resilience; design-for-sustainability; high-tech electronics plant; system composition; PLS-SEM

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1. Introduction

The development of high-tech electronics plants, which are pivotal in manufacturing lithium batteries, photovoltaics, semiconductor chips, etc., has increasingly aligned with sustainable development principles [1]. These plants have not only embraced cutting-edge technologies, but have also integrated eco-friendly processes to minimize their environmental impact. They prioritize energy efficiency, waste reduction, and the use of sustainable materials, aligning with the global goals of reducing carbon footprints and promoting environmental stewardship. The synergy in these high-tech sectors, especially in applications like electric vehicles and renewable energy systems, further underscores the role of these plants in advancing sustainable technologies. As a result, high-tech electronics plants are not just hubs of innovation and production, but are also exemplars of sustainable manufacturing, contributing positively to various industries and the environment.

Fires in high-tech electronics plants present serious risks, including threats to human safety, loss of life and property, environmental damage, supply chain disruptions, and data loss or cybersecurity breaches. For example, on 4 September 2013, an explosion occurred in the No. A clean room on the second floor of the wafer factory of Wuxi SK Hynix Semiconductor (China) Co., Ltd., followed by chain explosions and fires. Since the company is the third largest memory manufacturer in the world and its output accounts for 13% of the global memory market, the accident shocked the global technology community. Twenty days after the fire, global memory prices jumped 42% [2]. These high-tech electronics plant facilities house valuable equipment, sensitive data, and hazardous materials, making it crucial to prioritize fire prevention, detection, and mitigation measures. Implementing comprehensive fire safety protocols, training employees, and maintaining effective fire suppression systems are essential to minimize these risks and safeguard personnel, assets, and the environment. Therefore, fire resilience in high-tech electronics plants is crucial for ensuring personnel safety, protecting valuable assets, maintaining business continuity, minimizing environmental impact, upholding reputation, and complying with legal obligations.

The current fire resilience research mainly focuses on residential buildings, subway systems, bridges, etc. [3,4], and there is a lack of related research that fully considers the characteristics of high-tech electronic plants. In previous research, due to the nature of high public participation in civil buildings and infrastructure, the technical, organizational, social, and economic (TOSE) method and related models were frequently used to analyze fire resilience indicators [5]. However, due to the lower public participation and higher complexity of the production systems and processes, the existing models are not suitable for the fire resilience analysis of high-tech electronic plants. It is essential to deeply analyze the system composition of high-tech electronic plants and its influence on the formation of fire resilience [6]. Moreover, the organizational measurements, from prevention and resistance to recovery, are also crucial to developing fire resilience.

The aim of this research is to investigate the system composition mechanism and organizational influence factors that contribute to fire resilience in high-tech electronics plants, and further provide insights into the complex nature of these plants and how various elements of the system composition interact to enhance fire resilience to improve sustainability. The approach begins with a comprehensive literature review on both fire resilience and sustainable practices within industrial settings. Then, hypotheses based on the research gaps are identified. The methodology involves an industrial survey with expert interviews and questionnaire investigation, as well as the use of partial least squares structural equation modeling (PLS-SEM) for data analysis. The findings offer a dual perspective on fire safety and sustainability, leading to actionable recommendations for industry practices that prioritize both safety and environmental stewardship.

2. Theoretical Background

2.1. Fire Resilience in High-Tech Electronics Plants for Sustainable Development

Resilience in high-tech electronics plants is crucial for sustainable development, as it ensures the continuity and efficiency of operations essential to the global economy while minimizing environmental impact and resource depletion [7–9]. By adopting resilient practices, such as advanced fire safety measures, sustainable waste management, and energy-efficient technologies, these facilities not only safeguard against operational disruptions and potential environmental damages, but also contribute to the sustainable use of resources [10–12].

Resilience theory has evolved to provide a comprehensive understanding of how systems can effectively respond to disturbances, shocks, or adverse events [13,14]. The theory encompasses various dimensions, with one notable framework being the robustness, redundancy, resourcefulness, and rapidity (4R) model [15]. Robustness refers to a system's ability to withstand disruptions and maintain its essential functions [16]. Redundancy involves having backup or duplicate components to ensure system functionality in case of failures [17]. Resourcefulness focuses on the system's capacity to mobilize and effectively utilize resources during disruptions. Rapidity pertains to the speed and efficiency of system recovery after a disruption occurs. Design for safety is an approach that integrates safety considerations into the design process of systems, products, or infrastructure [18]. It aims to prevent or minimize hazards and risks by implementing safety features and hazard mitigation strategies, as well as considering human factors. Design for safety involves proactive planning [19], risk assessment [20], and the incorporation of safety standards and regulations [21], in order to enhance the overall safety and resilience of a system. In the context of resilience, a series of mathematical models and methods have been developed to evaluate resilience. For example, Bayesian networks can be utilized to assess risks, evaluate the impact of different factors on system performance, and support decision-making processes by considering multiple variables and their interdependencies [4,22].

Fire resilience in the construction industry refers to the ability of buildings, infrastructure, and construction systems to withstand and recover from fire incidents [4,22]. It involves designing and implementing measures to prevent, mitigate, and manage fire risks, ensuring the continuity of essential functions and minimizing the impact of fires on people, property, and the environment. Previous research mainly focuses on residential buildings [23], subway systems [3,24], bridges [25,26], forest areas, etc. [27,28].

Himoto and Suzuki [29] developed a multilayer domain model to evaluate the fire toughness of buildings using the toughness function to calculate the building damage rate. Wang et al. [30] introduced resilience theory into bridge fire safety management, proposed the concept of bridge fire resilience, and established a model to evaluate bridge fire resilience. Based on resilience theory, Huang Yajiang et al. [31] established a fuzzy comprehensive evaluation model for metro fire resilience systems based on the four dimensions of personnel, environment, equipment, and management. Tang et al. [3] came up with a systematic framework for the identification, evaluation, and optimization of metro fire resilience, and developed resilience optimization strategies for different service life periods of subways to continuously optimize their disaster resistance. Unlike the four-staged framework of fire resilience [32] in other civil infrastructures with higher public participation and without continuously running production systems, the essential capacities for high-tech electronics plants are related to three stages: the absorption capacity to resist and absorb external interference in the disaster preparation stage; the adaptive capacity in the emergency response stage; and the capacity to quickly recover to an acceptable level in the post-disaster recovery stage, as shown in Figure 1. Organizational and managerial factors are critical in most fire resilience research [3,31], and they are also included in the resilience formation system of high-tech electronics plants. Besides, the system composition and the joint operation of subsystems have a significant influence on the fire resistance of high-tech electronics plants, which is also an important aspect that has not been explored in previous studies. This research extracted measurement items from the literature as components to constitute the fire resilience capacity, as shown in Table 1.

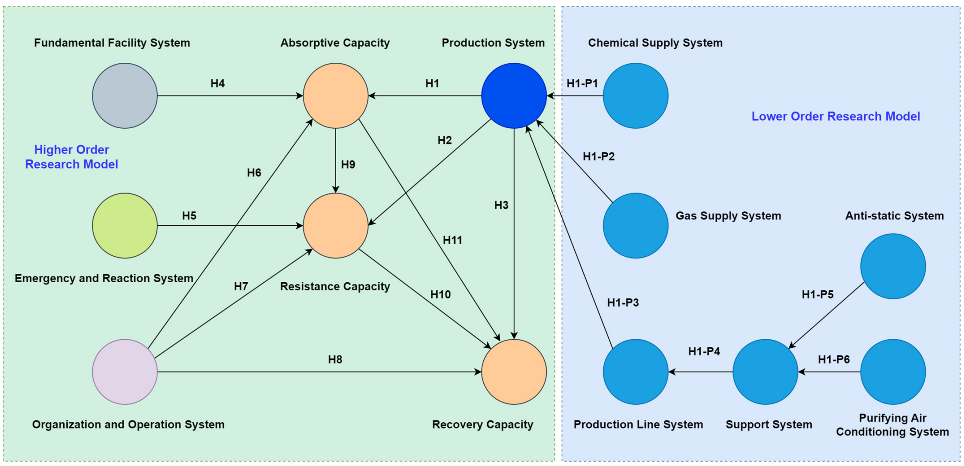

Figure 1. Research model with hypotheses.

Table 1. Construct definition from resilience capacity perspective.

Construct	Indicator Code	Indicator Definition	Reference
Absorptive capacity (ABS)	Abs1	Technical capabilities for fire prevention, including technical reserves such as daily monitoring, early warning, and real-time alarm	[22,29]
	Abs2	Organizational and managerial capabilities and organizational management systems for fire prevention	[3,33]
	Abs3	Production and operation environment for fire prevention	[22,34]
Resistance capacity (RES)	Res1	Technical system and technical capabilities for fire fighting and emergency rescue	[22,35]
	Res2	Organizational management system and organizational management capabilities for fire fighting and emergency rescue	[3,33]
	Res3	External resource configuration for fire and rescue	[3,22]
Recovery capacity (REC)	Rec1	Technical system and technical capabilities for the restoration of production and operations after a fire	[4,29]
	Rec2	Organizational management system and organizational management capabilities for the restoration of production and operations after a fire	[3,34]
	Rec3	External resource configuration for the restoration of production and operations after a fire	[4,29]

2.2. System Composition of High-Tech Electronics Plants

According to different system functions, the high-tech electronics plant system can be divided into four subsystems: the fundamental facility system, production system, emergency and reaction system, and the organization and operation system. In addition to the production line system, the production system also needs chemical supply systems and gas systems to provide power, an anti-static system, and an air conditioning purification system to maintain the stability of the production environment. This research extracted measurement factors from the literature and interviews as components to constitute these subsystems, as shown in Table 2.

Table 2. Construct definition from system composition perspective.

	Construct	Code	Definition	
Higher order construct	Fundamental facility system (FFS)	Essential infrastructure and systems that support the operations and functions of high-tech electronics plant facilities		
		PfsAbs1	Reasonability and effectiveness of fire protection compartment	[3,33,36,37]
		PfsAbs2	Fire protection performance of building materials and structures	[3,30,34,36,37]
		PfsRes1	Availability of fire lanes	[3]
		PfsRes2	Reasonability and effectiveness of fire evacuation routes	[3,36,37]
		EsAbs1	Availability of electrical protective devices	[31,38]
		EsAbs2	Availability and arrangement suitability of fire detectors	[35,38]
		EsRes1	Availability and effectiveness of automatic fire alarm and control system	[3,29,34,37]
		EsRes2	Availability and arrangement suitability of emergency lighting and evacuation signs	[3,37]
Higher order construct	Production system (PS)	Manufacturing processes, operations and environment used to produce electronic components and devices		
Lower order construct	Production line system (PLS)	PsAbs1	Fire protection measures for production processes	[35,39]
		PsAbs2	Fire prevention treatment of the interface of the production equipment	
		PsRec1	The ability and speed to restore key functions	
	Gas supply system (GS)	GsAbs1	Leak-proof capability of the gas supply system	[35]
		GsAbs2	Gas leak detection and alarm capability	
		GsRes1	Arrangement suitability of fire-arresting equipment and explosion-proof equipment for the gas supply system	
	Chemical supply system (CS)	CsAbs1	Leak-proof capability of the chemical supply system	From interview
		CsAbs2	Chemical products leak detection and alarm capability	
		CsRes1	Arrangement suitability of fire arresting equipment for the chemical supply system	

Table 2. *Cont.*

	Construct	Code	Definition	
	Purifying air conditioning system (PAS)	PasAbs1	Cleanliness of air environment	From interview
		PasAbs2	Stability of air temperature	
	Anti-static system (AS)	AsAbs1	Availability of electrostatic removal facilities	From interview
Higher order construct	Emergency and reaction system (ERS)	Real-time responsive fire suppression systems to extinguish or control the fire		
		WsRes1	Availability and arrangement suitability of fire water supply facilities and equipment	[29,31,34,36,37]
		WsRes2	Timely response of fire water supply facilities and equipment	[29,34]
		WsRec1	The ability and speed to restore the water supply function	[29,34]
		VsRes1	Availability and arrangement suitability of fire ventilation and smoke extraction system	[3,33,36]
		VsRes2	Timely response of fire ventilation and smoke extraction system	[35]
Higher order construct	Organization and operation System (OS)	OsAbs1	Safety of fire operation of maintenance personnel	[3]
		OsAbs2	Safety inspection of equipment and facilities	[3]
		OsAbs3	Fire emergency drill and safety training	[3,36,39]
		OsAbs4	The feasibility of a fire emergency plan	[3]
		OsAbs5	Safety of production personnel operation	[3]
		OsRes1	Emergency and response capacity of managers	[3]
		OsRes2	Safety of protective equipment for production personnel	[35,38]
		OsRec1	Timeliness of equipment and facilities maintenance	[3]

Currently, research on fire safety management in high-tech electronic plants mainly focuses on fire risk assessment and fire protection design [23,29,40,41]. However, insufficient exploration of the system composition of high-tech electronics plants has led to an unclear understanding of the features of fire protection in this specific production situation. At the same time, there is also a lack of research on fire protection organizational management systems from a sustainable perspective, resulting in the importance of organizational management in the formation of fire resilience not being reflected. Therefore, conducting in-depth research on the system resilience of high-tech electronics plants by combining system composition and organizational management is essential.

3. Hypothesis Development and Model Establishment

The formation of the absorptive capacity, resistance capacity, and recovery capacity of a high-tech electronics plant is influenced by its subsystems. The internal factors of the subsystem also affect the capabilities of the high-tech electronics plant at each stage by affecting the performance of the system. An initial research model based on the literature review and industrial interviews is presented in Figure 1.

The research model proposed in this paper is based on the resilience theory and the high-tech electronics plant system composition. Since the production system is crucial in the high-tech electronics plant, a hypothetical model with a two-level structure is developed in this research. The higher order model explores the resilience formation mechanism, and the lower order model explores the internal mechanism within the production system. According to the research model, the hypotheses about higher order constructs are proposed from H1 to H11. Meanwhile, there are a series of hypotheses, i.e., H-P1 to H-P6 within the production system proposed, as shown in Table 3.

Table 3. Hypotheses development.

Hypothesis	Description
H1	High performance of the production system is likely to improve the absorptive capacity of the high-tech plant.
H2	High performance of the production system is likely to improve the resistance capacity of the high-tech plant.
H3	High performance of the production system is likely to improve the recovery capacity of the high-tech plant.
H4	High performance of fundamental facility system is likely to improve the absorptive capacity of the high-tech plant.
H5	High performance of emergency and reaction system is likely to improve absorptive capacity of the high-tech plant.
H6	High performance of organization and operation system is likely to improve the absorptive capacity of the high-tech plant.
H7	High performance of organization and operation system is likely to improve the resistance capacity of high-tech plant.
H8	High performance of organization and operation system is likely to improve the recovery capacity of the high-tech plant.
H9	High performance of absorptive capacity of the high-tech electronics plant is likely to enhance the resistance capacity of the high-tech plant.
H10	High performance of resistance capacity of the high-tech electronics plant is likely to enhance the recovery capacity of the high-tech plant.
H11	High performance of absorptive capacity of the high-tech electronics plant is likely to enhance the recovery capacity of the high-tech plant.
H-P1	The performance of the production system is positively associated with the performance of the chemical supply system.
H-P2	The performance of the production system is positively associated with the performance of the gas supply system.
H-P3	The performance of the production system is positively associated with the performance of the production line system.
H-P4	The performance of the production line system is positively associated with the performance of the support system.
H-P5	The performance of the support system is positively associated with the performance of the anti-static system.
H-P6	The performance of the support system is positively associated with the performance of the purifying air conditioning system.

4. Materials and Methods

In this research, we employed a two-stage interview process alongside a questionnaire survey. The initial interviews were designed to formulate the questionnaire, and the subsequent interviews served to corroborate the statistical findings post-hypothesis testing.

The methodology also included the following five-step approach for gathering data, i.e., materials, pertinent to fire safety management in high-tech electronics manufacturing plants:

(1) First phase interview and questionnaire design: An initial questionnaire with 50 questions was grounded in the fire resilience literature, fire safety management of high-tech electronics plant literature, and standard specifications for high-tech electronics plants, and combined the results from the industry interviews.
(2) Pre-test for questionnaire development: After the first phase of interviews, we adjusted the order of partial questions to make them easier for interviewees to understand. The refined questionnaire underwent a pre-test involving 25 valid samples, aimed at further enhancing its quality. The outcomes of this pre-test indicated that the questionnaire was effectively structured and ready for broader deployment.
(3) Data collection by the formal questionnaire survey: A formal questionnaire with 50 questions survey was conducted to collect a larger sample.
(4) Model evaluation and hypotheses testing: Structural equation modeling (SEM) has been extensively employed in theoretical explorations and empirical validations in various research areas [42]. As an alternative to the classical covariance-based SEM (CB-SEM), partial least squares SEM (PLS-SEM) is a recent, widely used method that maximizes the explained variance of the dependent latent constructs instead of constructing a theoretical covariance matrix [43]. PLS-SEM can be used to estimate complex relationships and emphasize prediction without imposing high demands on data or requiring a specification of relationships. Therefore, PLS-SEM was employed in this study to validate the research model and test the proposed hypotheses [44–46].
(5) Second phase interview: The interview was conducted to provide qualitative evidence for the statistical results generated by the PLS-SEM calculation.

The first phase of our study included interviews with six seasoned experts, each with a background in one of four major fields: HVAC, water supply and drainage, electrical, or field operation and maintenance; each expert had over ten years of experience. Their feedback was instrumental in validating the content of our initial questionnaire. Subsequently, two additional experts in management were consulted to refine the questionnaire, focusing on correcting any items that were unclear or inaccurately phrased.

For the questionnaire survey, we ensured that the respondents were different from those who participated in the initial and follow-up interviews. The questionnaire featured a five-point Likert scale for responses, ranging from "strongly disagree" (score 1) to "strongly agree" (score 5), and included a specific question to filter out responses from individuals lacking adequate expertise. The participants were also encouraged to consider their work habits when responding. This online survey was conducted from 18 April to 22 June 2023, and we collected 84 responses, achieving a 51% response rate.

The respondents were considered to be professionals with relevant work experience in high-tech plants and basic understanding about fire safety. Nine respondents' questionnaires were rejected because they did not have related experience. Meanwhile, four respondents' questionnaires were excluded because of unqualified data. The final dataset contained 71 valid respondents. The details of the respondents are shown in Table 4. The percentages in the table represent the ratio of the number of respondents in each category to the total number of respondents. Since the first item type allows for multiple selections, the sum of these ratios exceeds 100%.

This study utilized PLS-SEM for research model validation, employing the SmartPLS software (Version 4.1.0.0). Subsequently, the second phase interviews were conducted with the initial interviewees. Their insights on the tested hypotheses were instrumental in juxtaposing real-world scenarios with the statistical outcomes, providing a deeper understanding of both consensus and discrepancies in the findings.

Table 4. Respondent details.

Personal Attribute	Categorization	Number of Respondents	Percentage (%)
Project types	Semiconductor	50	70.4%
	Chip	38	53.5%
	Lithium battery	38	53.5%
	Others	20	28.2%
Work position	Management	32	45.1%
	Production	4	5.6%
	Power supply	3	4.2%
	Construction	19	26.8%
	Others	13	18.3%
Working experience	<5 years	12	16.9%
	5–9 years	14	19.7%
	10–19 years	26	36.6%
	20–30 years	14	19.7%
	>30 years old	5	7%
Related high-tech electronics plant fire experience	Experienced	14	19.7%
	Unexperienced but well-understood	27	38%
	General understanding	30	42.3%
Age	<25 years old	6	8.5%
	25–34 years old	21	29.6%
	35–44 years old	25	35.2%
	45–55 years old	14	19.7%
	>55 years old	5	7%
Gender	Male	60	84.5%
	Female	11	15.5%
Academic qualifications	Junior college and below	11	15.5%
	Undergraduate	44	62%
	Postgraduate	16	22.5%

5. Results

5.1. Measurement Model Evaluation

An evaluation of the indicators in the research model was required. All of the indicators involved in our model are reflective. The indicator reliability, internal consistency reliability, convergent validity, and discriminant validity were evaluated for this reflective measurement model [43,46]. Table 5 provides the evaluation results of the indicator reliability, internal consistency reliability, and convergent validity. Outer loadings, which are empirically suggested to be more than 0.7, are commonly used to assess indication dependability. An ideal minimum factor loading value for an exploratory research model is 0.6 to 0.7 [46]. In our measurement model, all of the indicators have qualified loadings and respectively show significance. To test the internal consistency reliability, Cronbach's α and CR (composite reliability) are adopted. Cronbach's α is treated as the most conservative criterion, while CR represents a more liberal criterion. Cronbach's α values are required that are higher than 0.7, and the CR values of 0.60 to 0.70 in the exploratory research are regarded as satisfactory. All of the indicators represent good internal consistency reliability. To verify the convergent validity of the measurement model, the average variance extracted (AVE) of the measured constructs is necessary, and the acceptable minimum value of AVE is 0.36 to 0.5 [43]. All of the constructs represent good convergent validity. Besides, the

Fornell–Larcker criterion is suggested to evaluate the discriminant validity of the reflective measurement model. Table 6 shows the results of the discriminant validity evaluation.

Table 5. Evaluation of the measurement model.

Construct	Indicator Reliability				Internal Consistency Reliability		Convergent Validity
	Indicator	Loading	T-Value	Significance	Cronbach's α	CR	AVE
Absorptive Capacity (ABS)	Abs1	0.872	21.442	$p < 0.001$	0.859	0.914	0.780
	Abs2	0.896	23.846	$p < 0.001$			
	Abs3	0.882	13.007	$p < 0.001$			
Resistance Capacity (RES)	Res1	0.797	11.313	$p < 0.001$	0.764	0.864	0.680
	Res2	0.819	9.419	$p < 0.001$			
	Res3	0.856	17.344	$p < 0.001$			
Recovery Capacity (REC)	Rec1	0.879	22.381	$p < 0.001$	0.867	0.918	0.789
	Rec2	0.891	16.939	$p < 0.001$			
	Rec3	0.895	18.089	$p < 0.001$			
Production System (PS)	PsAbs1	0.768	13.275	$p < 0.001$	0.912	0.927	0.525
	PsAbs2	0.797	12.798	$p < 0.001$			
	PsRec1	0.709	9.068	$p < 0.001$			
	CsAbs1	0.845	15.213	$p < 0.001$			
	CsAbs2	0.745	7.942	$p < 0.001$			
	CsRes1	0.795	11.933	$p < 0.001$			
	GsAbs1	0.825	14.550	$p < 0.001$			
	GsAbs2	0.824	15.282	$p < 0.001$			
	GsRes1	0.790	10.857	$p < 0.001$			
	PasAbs1	0.363	2.419	$p < 0.016$			
	PasAbs2	0.440	2.859	$p < 0.004$			
	AsAbs1	0.597	4.935	$p < 0.001$			
Fundamental Facility System (FFS)	EsAbs1	0.866	14.976	$p < 0.001$	0.918	0.933	0.612
	EsAbs2	0.791	13.528	$p < 0.001$			
	EsRec1	0.816	15.425	$p < 0.001$			
	EsRes1	0.893	15.542	$p < 0.001$			
	EsRes2	0.785	10.054	$p < 0.001$			
	PfsAbs1	0.516	4.159	$p < 0.001$			
	PfsAbs2	0.776	13.209	$p < 0.001$			
	PfsRes1	0.788	8.876	$p < 0.001$			
	PfsRes2	0.754	7.431	$p < 0.001$			
Emergency and Reaction System (ERS)	VsRes1	0.723	0.000	$p < 0.001$	0.834	0.883	0.603
	VsRes2	0.750	8.656	$p < 0.001$			
	WsRec1	0.860	15.447	$p < 0.001$			
	WsRes1	0.690	6.069	$p < 0.001$			
	WsRes2	0.845	12.985	$p < 0.001$			

Table 5. *Cont.*

Construct	Indicator Reliability				Internal Consistency Reliability		Convergent Validity
	Indicator	Loading	T-Value	Significance	Cronbach's α	CR	AVE
Organization and Operation System (OS)	OsAbs1	0.815	11.121	$p < 0.001$	0.908	0.927	0.616
	OsAbs2	0.583	4.985	$p < 0.001$			
	OsAbs3	0.671	6.067	$p < 0.001$			
	OsAbs4	0.853	20.444	$p < 0.001$			
	OsAbs5	0.835	12.665	$p < 0.001$			
	OsRec1	0.839	20.227	$p < 0.001$			
	OsRes1	0.740	7.413	$p < 0.001$			
	OsRes2	0.891	30.482	$p < 0.001$			

Table 6. Fornell–Larcker criterion (latent variable correlations) for discriminant validity evaluation.

	ABS	RES	REC	PS	FFS	ERS	OS
ABS	0.883 *						
RES	0.835	0.824 *					
REC	0.855	0.878	0.888 *				
PS	0.727	0.749	0.739	0.724 *			
FFS	0.595	0.617	0.632	0.772	0.783 *		
ERS	0.643	0.723	0.664	0.757	0.644	0.777 *	
OS	0.611	0.724	0.753	0.766	0.658	0.499	0.785 *

Note: * represents the square root of the latent construct's AVE.

5.2. Structural Model Evaluation

To estimate the significance of path coefficients and test the hypotheses, a bootstrapping using 5000 bootstrap subsamples was conducted in the SmartPLS software package (Version 4.1.0.0). The path coefficients, the significance of path coefficients, and the coefficients of determination (R^2) are provided in Table 7.

Table 7. Structural model evaluation and key criteria.

Path	β	Mean	Std Dev	T-Value	Significance	R^2
Production System → Absorptive Capacity	0.585	0.602	0.258	2.265	$p < 0.024$	0.537
Production System → Resistance Capacity	−0.146	−0.155	0.156	0.931	$p < 0.352$	0.814
Production System → Recovery Capacity	−0.043	−0.032	0.181	0.238	$p < 0.812$	0.848
Fundamental Facility System → Absorptive Capacity	0.063	0.066	0.194	0.324	$p < 0.746$	
Emergency and Reaction System → Resistance Capacity	0.325	0.334	0.121	2.676	$p < 0.007$	
Organization and Operation System → Absorptive Capacity	0.121	0.115	0.204	0.594	$p < 0.553$	

Table 7. *Cont.*

Path	β	Mean	Std Dev	T-Value	Significance	R^2
Organization and Operation System → Resistance Capacity	0.362	0.394	0.122	2.966	$p < 0.003$	
Organization and Operation System → Recovery Capacity	0.262	0.253	0.145	1.813	$p < 0.070$	
Absorptive Capacity →Resistance Capacity	0.511	0.486	0.144	3.541	$p < 0.000$	
Resistance Capacity → Recovery Capacity	0.376	0.384	0.144	2.612	$p < 0.009$	
Absorptive Capacity → Recovery Capacity	0.412	0.396	0.142	2.906	$p < 0.004$	
Chemical Supply System → Production System	0.357	0.358	0.043	8.382	$p < 0.000$	
Gas Supply System → Production System	0.428	0.430	0.064	6.717	$p < 0.000$	0.993
Production Line System → Production System	0.335	0.328	0.079	4.221	$p < 0.000$	
Support System → Production Line System	0.871	0.874	0.032	27.245	$p < 0.000$	0.759
Anti-static System → Support System	0.378	0.379	0.023	16.303	$p < 0.000$	
Purifying Air Conditioning System → Support System	0.713	0.713	0.030	23.585	$p < 0.000$	

As shown in Figure 2, the path from the production system (PS) to the absorptive capacity (ABS) is strongly supported by collected data, and it is significant (β = 0.585, R^2 = 0.537, $p < 0.024$). The main path from the construct absorptive capacity (ABS) to resistance capacity (RES) to recovery capacity (REC) is also significant, which reflects the resilience formation mechanism in high-tech electronics plants. Meanwhile, fire resilience formation assumptions within production systems are all supported, as shown in Table 8.

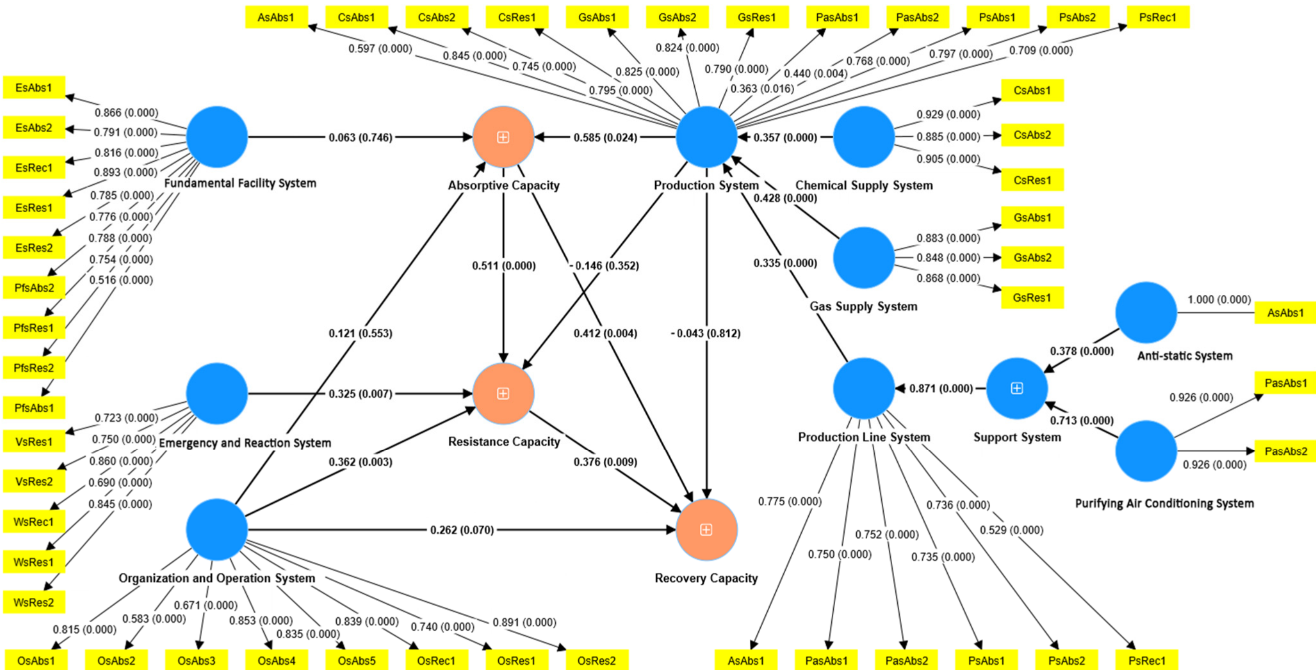

Figure 2. Test results of the research model.

Table 8. Results of hypothesis testing.

Hypothesis	Path	Result
H1	Production System → Absorptive Capacity	Supported
H2	Production System → Resistance Capacity	Not supported
H3	Production System → Recovery Capacity	Not supported
H4	Fundamental Facility System → Absorptive Capacity	Weakly supported
H5	Emergency and Reaction System → Resistance Capacity	Supported
H6	Organization and Operation System → Absorptive Capacity	Weakly supported
H7	Organization and Operation System → Resistance Capacity	Supported
H8	Organization and Operation System → Recovery Capacity	Supported
H9	Absorptive Capacity → Resistance Capacity	Supported
H10	Resistance Capacity → Recovery Capacity	Supported
H11	Absorptive Capacity → Recovery Capacity	Supported
H-P1	Chemical Supply System → Production System	Supported
H-P2	Gas Supply System → Production System	Supported
H-P3	Production Line System → Production System	Supported
H-P4	Support System → Production Line System	Supported
H-P5	Anti-static System → Support System	Supported
H-P6	Purifying Air Conditioning System → Support System	Supported

6. Discussion

This study innovatively assessed the formation of fire resilience in high-tech electronics plants from a system composition perspective, and explored organizational management constructs. Therefore, it is vital in both the theoretical and the practical sense to address their research gaps to advance our understanding of improving fire resilience in high-tech electronics plants or similar production environments for sustainable development. This research provides the following important implications:

(1) **Improving Fire protection design measures**

Implementing fire protection design measures in high-tech electronic plants is a critical step in aligning industrial safety with sustainable development goals. The following subsystems are crucial for sustainable fire protection design:

The integration of explosion-proof and flame-retardant systems is a proactive approach to mitigate the risk of fires and explosions, which are particularly pertinent in facilities dealing with volatile materials and high-energy processes. By preemptively addressing these risks, plants not only protect their assets and personnel, but also prevent potential large-scale environmental disasters that could arise from uncontrolled fires.

The use of fire-resistant materials in construction and design is crucial for safety, particularly in high-tech environments like those involving the silicon-slicing process. In this process, the risk of spontaneous silicon combustion and the complex nature of gas supply systems elevate the potential for fires and explosions. To mitigate these risks, the requirements for fireproof materials in clean rooms are more stringent than for other plant areas. For example, according to Chinese standards, the fire protection zone and evacuation distance of this area far exceed the requirements of GB 50016-2014 [47] in the Code for Fire Protection Design of Buildings [48]. Additionally, it is crucial to consider the risk of structural damage and instability due to explosions when choosing construction materials. This approach ensures a targeted and safer design for such specialized production facilities.

Advanced ventilation systems are another key component, which refer to sophisticated air management systems designed for high-tech environments, such as clean workshops. These systems are tasked with maintaining optimal air quality during normal operations, and are crucial in fire safety scenarios. According to GB 50016-2014 in the Code for Fire

Protection Design of Buildings, fire ventilation is not part of a general ventilation system, but is designed with detailed specifications, and can be turned on by both manual and automatic means. Fire supplementary air cannot be extracted directly from the outside, so clean air processed by a fresh air conditioning unit is used as fire supplementary air. An electric valve is installed on the branch air duct that is normally closed, and is automatically opened for fire protection. However, in practice, the opening mechanism of the electric valve still needs to be optimized. The current trigger opening state will only be automatically executed when a large fire occurs. However, in reality, it needs to be turned on earlier, requiring more sophisticated sensors and intelligent triggering algorithms.

Eco-friendly fire suppression systems further exemplify the marriage of safety and sustainability. Unlike traditional fire suppression methods, which can involve harmful chemicals or excessive water usage, eco-friendly systems use environmentally benign agents or advanced methods that are more effective and less damaging to the environment. These systems ensure that the necessary act of extinguishing fires does not lead to secondary environmental issues, such as water pollution or chemical runoff.

(2) **Sustainable and fireproof construction facility**

In high-tech electronics plants, the role of civil infrastructure elements like fireproof materials and fire exits, while fundamental for safety, extends to sustainable building practices. These elements, often compliant with regulatory requirements and industry standards, contribute to the plant's resilience by ensuring minimal environmental damage during emergencies.

Although they may not directly impact the core production system, their role in sustainable construction and energy efficiency is vital. The focus on eco-friendly materials and designs in these infrastructure elements reflects a broader commitment to sustainability, complementing the plant's resilience strategies focused on the production system.

(3) **Organizational management support**

The organizational management system in high-tech electronics plants plays a pivotal role in enhancing fire resilience, particularly through personnel training and awareness.

Firstly, well-trained staff are more adept at identifying potential fire hazards, thereby indirectly contributing to fire prevention. Their heightened awareness and understanding of fire risks can lead to more proactive measures in identifying and mitigating potential fire threats before they escalate.

Secondly, in the event of a fire, personnel trained in environmentally responsible emergency procedures are equipped to respond in a manner that not only prioritizes human safety, but also minimizes environmental damage. This approach is especially important in high-tech electronics plants, where fires can involve hazardous materials and have significant environmental repercussions. By managing these incidents effectively, the environmental impact of fires can be significantly reduced.

Moreover, the effectiveness of the organizational management system in promoting sustainable practices extends beyond emergency response. It encompasses broader aspects of operational excellence, such as energy management, waste reduction, and the sustainable use of resources. This holistic approach ensures that the plant operates efficiently, and in an environmentally conscious manner.

Furthermore, the commitment to training and awareness reflects a deeper organizational commitment to environmental responsibility. This commitment is often mirrored in corporate policies and practices, influencing a company's culture and setting standards for industry best practices.

7. Conclusions

Current research on fire safety in high-tech electronic plants primarily focuses on risk assessment and fire protection design. However, there is a gap in understanding the system composition and fire protection features specific to specialized production and operation environments. Additionally, the role of organizational management in fire resilience, especially from a sustainability standpoint, remains underexplored. Thus, it is crucial to integrate system composition and organizational management in studying the system resilience of high-tech electronics plants. Through a literature review, hypothesis development, an industrial survey, and PLS-SEM analysis, this research systematically explored the critical aspects of fire resilience in high-tech electronics plants through the lens of sustainable development. By examining the interplay of fire protection design measures, construction facilities, and organizational management, we have underscored the importance of integrating eco-friendly and safety-focused practices in these advanced manufacturing environments.

The findings emphasize that enhancing fire resilience in high-tech electronics plants goes beyond mere compliance with safety standards; it necessitates a holistic approach that incorporates three essential aspects: (1) fire protection design measure improvement, (2) sustainable and fireproof construction facility, and (3) organizational management support. Sustainable fire protection designs in high-tech electronic plants represent a holistic approach to resilience. They embody a forward-thinking strategy that prioritizes the safety of personnel and the protection of assets, while simultaneously upholding a strong commitment to environmental responsibility. Meanwhile, the role of the organizational management system in high-tech electronics plants is multifaceted. It is not just about training personnel for fire emergencies; it is about fostering a culture of safety, environmental stewardship, and operational excellence. By integrating these aspects, high-tech electronics plants can enhance their resilience in terms of fire safety, as well as their overall sustainable operations.

The recommendations provided in this study, based on comprehensive research and analysis, offer actionable insights for industry practitioners, highlighting the potential to not only safeguard against fire-related risks, but also to contribute positively to environmental conservation and social well-being. This research fills a significant gap in the current understanding of fire resilience, especially from a system composition perspective, and paves the way for future studies to delve further into the integration of sustainability in high-tech manufacturing sectors. Further studies could focus on the long-term impact of these practices on environmental conservation and social well-being. Additionally, expanding the scope to include different types of high-tech manufacturing sectors could provide a broader understanding of sustainable fire resilience strategies. This direction will enhance fire safety and contribute to the overall sustainability of high-tech manufacturing.

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