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Rework Quantification and Influence of Rework on Duration and Cost of Equipment Development Task

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Abstract: Rework is a sub-task within equipment development tasks that is revised after initial completion to meet task requirements. Some sub-tasks require multiple rework iterations due to their uncertainty and complexity, or the technology and process needs of the overall task, resulting in inefficient task implementation and resource wastage. Therefore, studying the impact of rework iterations on the duration and cost of development tasks is worthwhile. This study divides rework into foreseeable and hidden types and uses several methods to express and quantify their parameters. The main influencing factors in rework iterations—the uncertainty and complexity of the development task—are quantitatively analyzed. Then, mathematical and mapping models of the dependence between sub-tasks, uncertainty, complexity, and rework parameters are established. The impacts of rework type and rework parameters on the duration and cost of equipment development tasks are analyzed via simulation based on the design structure matrix (DSM). Finally, an example is used to illustrate the influence of different rework types and rework parameters on development tasks' duration and cost. The results show that the duration and cost of development tasks are greater, their volatility range is wider, and the distribution is more dispersed when both foreseeable and hidden rework are considered.

Keywords: equipment development task; foreseeable rework; hidden rework; uncertainty; complexity

1. Introduction

Equipment development is the process of obtaining a combination of equipment, or equipment with a specific function, through purposeful, planned, and constantly repeated exploration, testing, demonstration, and trial production. Equipment development is the process of upgrading to promote the sustainable development of the equipment manufacturing industry. Estimating the duration, cost, and resources required for rework iterations in an equipment development task is impossible. Thus, many equipment development tasks run over schedule, incur cost overruns, and must even be suspended, resulting in a great waste of human, material, financial, and other resources. Promoting the sustainable development of the equipment manufacturing industry requires the consideration of project duration, cost, and other indicators to ensure an effective analysis, evaluation, and selection of the equipment development task plan [1]. An equipment development task requires a large investment of resources and a huge amount of work to be executed within a short timeframe [2]. Completing a development task requires cooperation between many development teams and a high degree of innovation. An equipment development task is very complicated and carries a high level of uncertainty. Due to the influence of rework, overlap, and other factors, development task duration and cost will fluctuate widely and are difficult to effectively predict, manage, or control. The uncertainty and complexity of equipment development tasks are the main factors affecting rework iterations, which occur often because of those factors [3]. In general, rework iterations have a positive effect on the successful completion of equipment development tasks, but they increase their duration and cost [4,5]. Accurately estimating duration and cost requires an accurate analysis of the uncertainty and complexity of the proposed equipment development task. We establish a quantitative relation model measuring the degrees of dependence between sub-tasks, uncertainty, complexity, and rework parameters and then analyze the influence of rework parameters on the duration and cost of an equipment development task.

Next, this article discusses the connotations, classification, and main influencing factors of equipment development task rework and analyzes methods of evaluating its main influencing factors. Then, a mathematical model and mapping model of the relationships of dependence between sub-tasks, uncertainty, complexity, and rework parameters are established. Then, a development task simulation model is established based on the DSM. Finally, an example is used to illustrate the influence of different rework types and rework parameters on the duration and cost of development tasks.

2. Literature Review

The degree of information dependence between sub-tasks is an important factor to consider in a quantification of an equipment development task. The DSM is a structured modeling tool used to represent the dependencies between elements in a domain [6,7]. The DSM describes the serial, parallel, coupled, or iterative relationships among activities from the perspective of information flow, and provides a concise and clear matrix representation for complex processes. It can be used to analyze the dependencies, rework iterations, and other issues between sub-tasks in development tasks [8]. Steward applied the DSM to the analysis and management of complex systems [9]. Since then, DSM has been widely used for the process optimization, collaborative design, and risk analysis of products [7,10]. The DSM can be used to analyze dependencies between elements in a domain, but it is necessary to analyze the dependencies of elements between different domains. Scholars have also studied mapping models of the relationships between elements in different domains and constructed domain mapping matrices (DMMs), multi-domain matrices (MDMs), and extended domain mapping matrices (EDMMs), which can be used to describe and quantify the dependencies between elements in multiple domains (such as product domain–functional domain, functional domain–organizational domain, and team–product–function relationships) [7,11].

Uncertainty is a main factor causing rework iterations in equipment development tasks and thus needs to be considered in rework quantification. The uncertainty of an equipment development task is influenced by many factors and has a wide range of causes. The potential for certain events to occur, lack of information, and ambiguity will lead to uncertainties in equipment development tasks. Planning and implementing equipment development tasks require the effective identification and management of the main influencing factors of uncertainty [12]. Uncertainty can be divided into technical, market, environmental, process, and interrelation types [13]. Uncertainty can be further divided into variation, foreseeable uncertainty, unforeseeable uncertainty, and chaos types based on its degree [14]. Jensen et al., [15] constructed a model of the relationship between projects and the environment caused by uncertainty factors, identified the main factors that cause project uncertainty, and analyzed their influence on project structure, process, and operational effect. Li et al., [16] analyzed three uncertainties: the activity, the design plan, and the environment. Their model quantitatively described the impact of these three uncertainties on rework probability in the development of new products. Yang et al., [17] used parameters such as iterative probability, iteration length, number of iterations, and learning curve to characterize the uncertainty of product development and used overlapping levels to characterize the ambiguity of product development. They built a discrete event simulation model based on Arena to simulate a research and development (R&D) project and study how uncertainty related to iteration and ambiguity related to overlaps affected product development duration.

Complexity is another main factor that causes rework iterations in equipment development tasks and that needs to be considered in rework quantification. Complexity can be of technological, organizational, content, informational, objective, or environmental kinds. The current focus of the literature's research on project complexity is organizational and technical complexity [18,19]. Baccarini [20] discussed the meaning and specific influencing factors of project complexity from the perspectives of organization, technology, and information. Lu et al., [21] examined large-scale projects with large numbers of sub-tasks and high degrees of complexity and focused on tasks and organizational perspectives to investigate a complexity measurement model that considered hidden workloads. The Shanghai World Expo construction project was selected as a case study with which to verify the effectiveness of the proposed method. Many scholars have studied the complexity evaluation of R&D tasks from various perspectives and using various methods, but no uniform method of evaluating the complexity of R&D tasks has yet been established. Bosch-Rekveldt et al., [22] proposed a complexity measurement model for the development phase of engineering projects. Large-scale engineering products and equipment are very complex and generally have a long R&D cycle. Design changes often occur in the R&D process, which can result in schedule or cost overruns. Rebentisch et al., [23] evaluated the impact of changes in the technical systems of R&D projects as well as their impact on costs and duration based on structural complexity.

Development task simulation based on DSM is an important method of analyzing the operation effect of a development task. Many scholars have carried out extensive research on this problem. Browning et al., [24] built the first DSM-based product development process architecture simulation model, which laid the foundation for DSM-based R&D task simulation. The model allows us to consider factors such as rework iteration and learning effect and to estimate the duration of R&D projects based on discrete event simulation [25]. Large amounts of resources are required in the implementation of equipment development tasks. Cho et al., [26] conducted project simulations under resource-constrained conditions based on the DSM. Many factors influence the development of equipment, and most are uncertain. Zhang et al., [27] constructed a simulation model of development tasks under the influence of multiple uncertain conditions. Luo [28] evaluated the impact of product architecture on evolvability using simulation methods. Karniel et al., [29] constructed a DSM that reflects changes in the product development process and proposed a product development process management method based on multi-level modeling and simulation. The influence of rework iteration and change propagation on the product design process can be analyzed when a product development process changes based on a discrete event simulation model [30].

Much fruitful research has been conducted on rework quantization, uncertainty, complexity, and simulation in development tasks. For the quantification of rework parameters, the degrees of information dependence between sub-tasks are used to quantify the foreseeable rework parameters. Little research has been conducted on the influence of uncertainty and complexity on the rework parameters of equipment development tasks. Studies on how development task rework affects schedules and costs have considered only foreseeable rework, assuming that the rework probability is known, and the impact of hidden rework has not been considered. Equipment development tasks have many influencing factors, large uncertainties, and complex network structures. It is difficult to estimate the workload needed for rework, and its duration and costs fluctuate widely. To better evaluate, manage, and control equipment development tasks, it is necessary to further study the impact of sub-task rework on the duration and cost of equipment development tasks based on a classification of the influencing factors and quantitative methods of rework.

3. Connotation and Main Influencing Factors of Equipment Development Task Rework

3.1. Connotation and Classification of Rework

Rework is a sub-task within equipment development tasks that revises, improves, or perfects after initial completion to meet the requirements of the equipment development task. This occurs due to the coupling between sub-tasks, information changes, and errors during sub-task execution. The probability and impact of rework in some sub-tasks are foreseeable, although some sub-task rework may be random and difficult to anticipate. For this reason, the rework of sub-tasks in equipment development tasks can be divided into foreseeable and hidden rework tasks.

Foreseeable rework is caused by certain specific factors, such as sub-task coupling and information dependence. It can be predicted at the equipment development task planning stage, and the probability of occurrence and impact can be estimated. In the equipment development task planning stage, the foreseeable rework parameters are generally predictable, including the rework sub-tasks and sub-tasks that triggered the sub-task rework, the probability of rework occurrence, and the rework impact.

Hidden rework is caused by random factors such as mistakes in the development process and changes in requirements. This type of rework occurs randomly and cannot be predicted during the equipment development task planning stage. Sub-tasks with hidden rework, sub-tasks that cause hidden rework, hidden rework probability, and hidden rework impacts are all randomly generated.

3.2. Main Factors Affecting Rework

Many factors can affect the redevelopment of the equipment development task. The main ones are the development task's uncertainty and complexity.

3.2.1. Uncertainty

Uncertainty is the state in which people cannot, or do not, accurately grasp the full impact of future activities or events. It reflects a gap between objective reality and people's subjective knowledge [31].

Because of the complexity and uniqueness of each equipment development task, each task is different, and there is little historical experience or information that can be used for reference, making development tasks highly uncertain. The uncertainty of the equipment development task is affected by many factors, including market uncertainty, technical uncertainty, environmental uncertainty, and the uncertainty of the interrelationship between participating parties [13], as detailed below.

(1) Market uncertainty: Equipment development task participants may not have an accurate understanding of the actual market demand. A deep understanding of the development task and its market demand leads to continuous revisions of market demand estimates during the implementation of the equipment development task.
(2) Technical uncertainty: We need new technological breakthroughs in equipment development tasks. However, the application of new technologies or breakthroughs in new technologies is subject to considerable uncertainty and can lead to technological uncertainties in equipment development tasks.
(3) Environmental uncertainty: Environmental uncertainty is caused by incomplete knowledge of the environment, especially the external environment, in which equipment development tasks occur [32,33].
(4) Uncertainties in the interrelationship between participating parties: Equipment development tasks require the collaboration of many participating parties. There are uncertainties in their relationships.
(5) Uncertainties caused by human factors: Uncertainty caused by human factors comprises uncertainty due to limited human capabilities, subjective prejudices, and even work negligence.
(6) Estimated uncertainty: Any equipment development task will involve the estimation of costs, duration, and quality, and such estimated data involve uncertainties [12].

The degree of sub-task uncertainty can be calculated based on the factors affecting it. The values for each factor are divided into 10 levels according to their characteristics. The larger the value, the higher the degree of sub-task uncertainty. The degree of uncertainty is calculated according to scores given by experts. The formula is

$$Uncertainty_i = \frac{\sum_{j=1}^{m} \omega_j x_{ij}}{m \times 10} \quad (1)$$

where $Uncertainty_i$ is the degree of uncertainty of sub-task i; x_{ij} is the score of the influencing factor j of sub-task i; ω_j is the weight of the influencing factor j; and m is the number of influencing factors.

3.2.2. Complexity

Complexity is another important factor in the rework of an equipment development task [19]. Complexity in an equipment development task consists of the sum of the complexity of the various sub-tasks and their interrelationships. The complexity of each sub-task consists of the complexity of the internal elements of the sub-task and the interrelationships among them. The influencing factors of the complexity of the equipment development task include technical, organizational, and environmental complexity, as well as information complexity, the complexity of the objectives, and the number of sub-tasks.

(1) Technical complexity: The complexity of a technology can be described by considering the integration of the technical components and technological innovation. In general, the higher the degree of integration and innovation, the higher is the complexity of the technology.
(2) Organizational complexity: Baccarin claims that organizational complexity originates from the difference and interdependence between units within an organization [20]. Organizational differences include horizontal, vertical, and spatial distribution differences.
(3) Number of sub-tasks: An equipment development task is a systematic project. A complete implementation process requires the coordination of various sub-tasks, resources, and other elements. The number of sub-tasks will directly affect the level of difficulty involved in coordinating the equipment development task.
(4) Complexity of sub-tasks: An equipment development task consists of many sub-tasks. In general, the more complex the sub-tasks, the more complex is the overall equipment development task.
(5) Information complexity: The information required for equipment development tasks includes both internal and external information. Internal information consists mainly of input from participating units, users, suppliers, and other divisions or departments. External information mainly consists of information acquired from government policies, the economic environment, and market conditions.
(6) Target complexity: An equipment development task must achieve not only targets such as duration, cost, and quality on a management level but also technical, economic, and security goals at the functional level, while also meeting the goals of national/regional economic development, social stability, and national defense security. Thus, development tasks have a diversity of goals, which are both interrelated and interactive.

The degree of complexity of a sub-task can be calculated using a method similar to that used to measure the degree of uncertainty. The formula is

$$Complexity_i = \frac{\sum_{k=1}^{n} \mu_k y_{ik}}{n \times 10} \quad (2)$$

where $Complexity_i$ is the degree of complexity of sub-task i; y_{ij} is the score of the influencing factor k of sub-task i; μ_k is the weight of the influencing factor k; and n is the number of influencing factors.

4. Confirmation of Rework Parameters and Development Task Simulation

This chapter introduces the representation and determination methods of rework parameters and the simulation process for development tasks. A list of the abbreviations used in this chapter is provided in Table 1.

Table 1. Summary table of abbreviations used in this chapter

Abbreviation	Explanation
DSM	design structure matrix
FRP	foreseeable rework probability
FRI	foreseeable rework impact
PHR	proportion of sub-tasks that may contain hidden rework
HRP	hidden rework probability
HRI	hidden rework impact
ARP	actual rework probability
ARI	actual rework impact
EMDM	extended multi-domain matrix
F_DSM	function design structure matrix
C_DSM	component design structure matrix
O_DSM	organization design structure matrix
EDMM	extended domain mapping matrix
FEL	future event list
WL	wait list

4.1. Representation of Rework Parameters

4.1.1. Representation of Foreseeable Rework Parameters

The interrelationships and rework parameters between sub-tasks of an equipment development task can be represented using the DSM. The elements of the DSM indicate that the corresponding task column of the element supplies or supports information for the corresponding row task. Given the development tasks of the n sub-tasks $T_i (i = 1, 2, 3, \cdots, n)$, element A_{ij} in the matrix indicates that sub-task T_j provides information to sub-task T_i. The values of the DSM elements that contain predictable rework information are defined as follows: $DSM_{ij} = 0$ indicates that there is no immediate predecessor or successor relationship between sub-task i and sub-task j; $DSM_{ij} = 1$ indicates that sub-task i is the immediate successor of sub-task i; and $DSM_{ij} = p, p \in (0, 1)$ indicates that sub-task i and sub-task j overlap with probability p.

The foreseeable rework probability (FRP) matrix describes the uncertainty of rework iterations and is represented by a certain rework probability. The element FRP_{ij} of the FRP matrix represents the probability that sub-task j will trigger the foreseeable rework of sub-task i.

The foreseeable rework impact (FRI) matrix denotes the impact of rework sub-tasks when predictable rework occurs. The element FRI_{ij} of the FRI matrix represents the proportion of the duration and cost of the foreseeable rework of sub-task i against its original duration and cost estimate, in cases when foreseeable rework is generated by sub-task j for sub-task i.

4.1.2. Representation of Hidden Rework Parameters

The hidden rework DSM is similar to the foreseeable rework DSM, but hidden rework is unforeseeable during the equipment development task planning stage, and it is not possible to determine which sub-tasks may incur hidden rework. We can use random methods to select the proportion of sub-tasks that may contain hidden rework (PHR) and the sub-tasks that will be reworked. On this basis, parameters such as hidden rework probability (HRP) and hidden rework impact (HRI) are generated randomly. The impact of hidden rework on equipment development tasks can be simulated through the DSM-based development task simulation. In the upper triangular matrix of the DSM, if an element's column may cause a rework of the element's row, the element is taken as 1;

otherwise, the element is taken as 0. The HRP and HRI are determined by a certain range of random numbers and distribution functions, respectively. Hidden rework parameters randomly generate a pseudo code, as shown in Figure 1.

```
for i = 1: n
    for j = 1: n
        if  rand > PHR
            HDSM_ij = 0   % Sub-task j does not trigger rework of sub-task i
            HRP_ij = 0
            HRI_ij = 0
        else
            HDSM_ij = 1   % Sub-task j may trigger rework of sub-task i
            HRP_ij = rand * HRPM_ij     %  HRPM_ij  is the upper limit of HRP_ij
            HRI_ij = rand * HRIM_ij     %  HRIM_ij  is the upper limit of HRI_ij
        end if
    end for
end for
```

Figure 1. Hidden rework parameters randomly generated pseudo code.

4.1.3. Representation of Actual Rework Parameters

Rework in the task-development process comprises two parts: foreseeable rework and hidden rework. Actual rework probability (ARP) includes FRP and HRP. Actual rework impact (ARI) includes FRI and HRI.

Assuming that FRP and HRP are independent of each other, ARP can be expressed as

$$ARP_{ij} = FRP_{ij} \cup HRP_{ij} = 1 - \left(1 - FRP_{ij}\right) \times \left(1 - HRP_{ij}\right) \quad (3)$$

where ARP_{ij} is the ARP of sub-task j trigger rework of sub-task i; FRP_{ij} is the FRP of sub-task j trigger rework of sub-task i; and HRP_{ij} is the HRP of sub-task j trigger rework of sub-task i.

Assuming that FRI and HRI are independent of each other, ARI can be expressed as

$$ARI_{ij} = FRI_{ij} \cup HRI_{ij} = 1 - \left(1 - FRI_{ij}\right) \times \left(1 - HRI_{ij}\right) \quad (4)$$

where ARI_{ij} is the ARI of sub-task j trigger rework of sub-task i; FRI_{ij} is the FRI of sub-task j trigger rework of sub-task i; and HRI_{ij} is the HRI of sub-task j trigger rework of sub-task i.

4.2. Determination of Rework Parameters

The equipment development task is a complex system. Its execution involves a certain degree of uncertainty and ambiguity [17]. Complexity and uncertainty are the main influencing factors in the rework of sub-tasks. Rework probability and rework impact are related to the complexity and uncertainty of the development task. The relationship between complexity, uncertainty, and rework probability is shown in Figure 2. In general, the higher the complexity of an equipment development task, the greater are the HRP and HRI. The greater the uncertainty, the greater are the FRP and FRI.

To quantify the rework parameters, we first analyze the main influencing factors in the complexity and uncertainty of the equipment development task. Complexity and uncertainty are evaluated, and the quantified values of the complexity and uncertainty levels of each sub-task are obtained.

Then, an extended multi-domain matrix (EMDM) is constructed; this is the "sub-task–component–function" EMDM, as shown in Figure 3a. EMDM can reflect the dependencies between components, functions, and corresponding sub-tasks. The function design structure matrix (F_DSM) reflects the interaction between functions. The component design structure matrix (C_DSM) reflects the input/output dependence of the key performance parameters between components. The extended domain mapping matrix (EDMM) reflects the dependencies between components, functions, and corresponding sub-tasks, that is, the dependencies of sub-tasks in implementing component related functions. The level of information dependence in the organization design structure matrix (O_DSM) can be derived by EMDM, as shown in Figure 3b. On this basis, O_DSM is normalized.

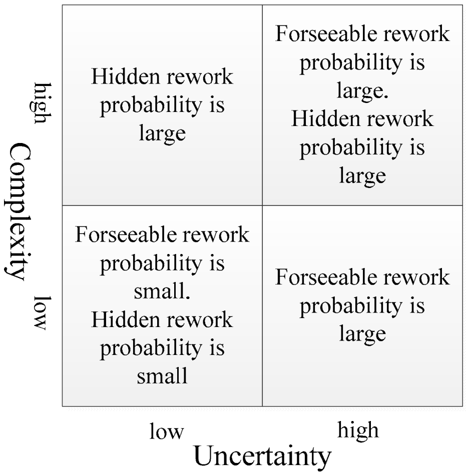

Figure 2. Relationship between rework probability and complexity and uncertainty.

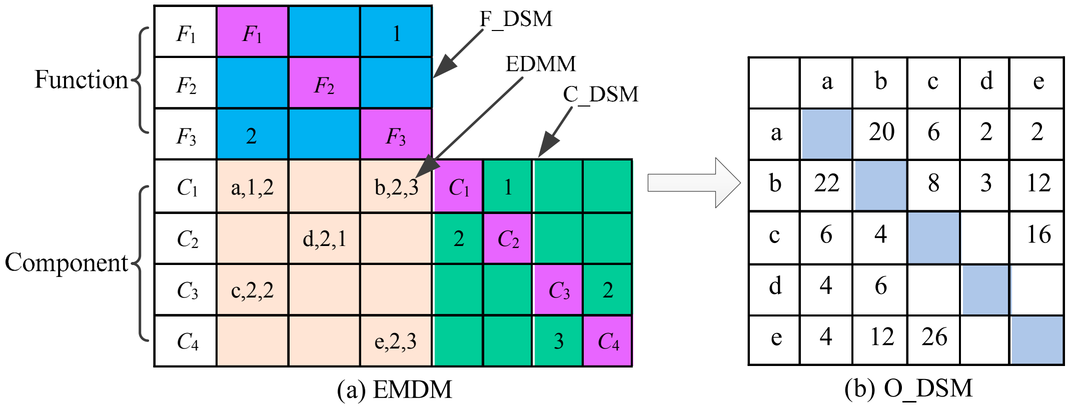

Figure 3. Organization design structure matrix (O_DSM) derivation process.

Finally, according to the degree of information dependency between sub-tasks, the FRP between sub-tasks is calculated by combining the degree of complexity and uncertainty of the sub-tasks that cause rework with the degree of complexity and uncertainty of the reworked sub-tasks. The formula is

$$FRP_{ij} = K \times \left[O\_DSM_{ij} \times \left(Uncertainty_i \times Complexity_i \times Uncertainty_j \times Complexity_j \right)^{\frac{1}{2}} \right]^{\frac{1}{3}} \tag{5}$$

where FRP_{ij} is the FRP of sub-task j trigger rework of sub-task i; O_DSM_{ij} is the normalized information dependence of sub-task i on sub-task j; $Uncertainty_i$ is the degree of uncertainty of sub-task i; $Complexity_i$ is the degree of complexity of sub-task i; $Uncertainty_j$ is the degree of uncertainty of sub-task j that causes rework; $Complexity_j$ is the degree of complexity of sub-task j that causes rework; and K is the adjustment factor.

The range of each hidden rework parameter can be obtained by mapping the complexity and uncertainty of the equipment development task to each hidden rework parameter. On this basis, each hidden rework parameter can be generated randomly.

4.3. Development Task Simulation

Development task simulation is an effective tool for analyzing the rework iterations during complex dynamic development tasks, as well as analyzing and evaluating the performance of the equipment development task through simulation data [17]. Because equipment development is highly complex and implies many uncertainties, it is difficult to analyze development tasks through mathematical modeling. Simulation tasks can be mimicked by discrete event simulation modeling [27]. A single simulation run flow diagram is shown in Figure 4. The future event table (FEL) is composed of the completion events for sub-tasks in order of the events; each element in the FEL represents a sub-task. When the FEL is not empty, this indicates that there are sub-tasks in the system that are executing. First, the first event is taken from the FEL, indicating that the sub-task corresponding to the event is completed, and the sub-task is deleted from the FEL. Then, it is determined whether the subsequent sub-tasks can be executed. The sub-tasks that can be executed are entered into the wait list (WL), and the sub-tasks in the WL are prioritized. Finally, it is determined which sub-tasks can enter the FEL according to resource constraints. When the FEL is empty, this indicates that all activities have been performed, and the simulation is over.

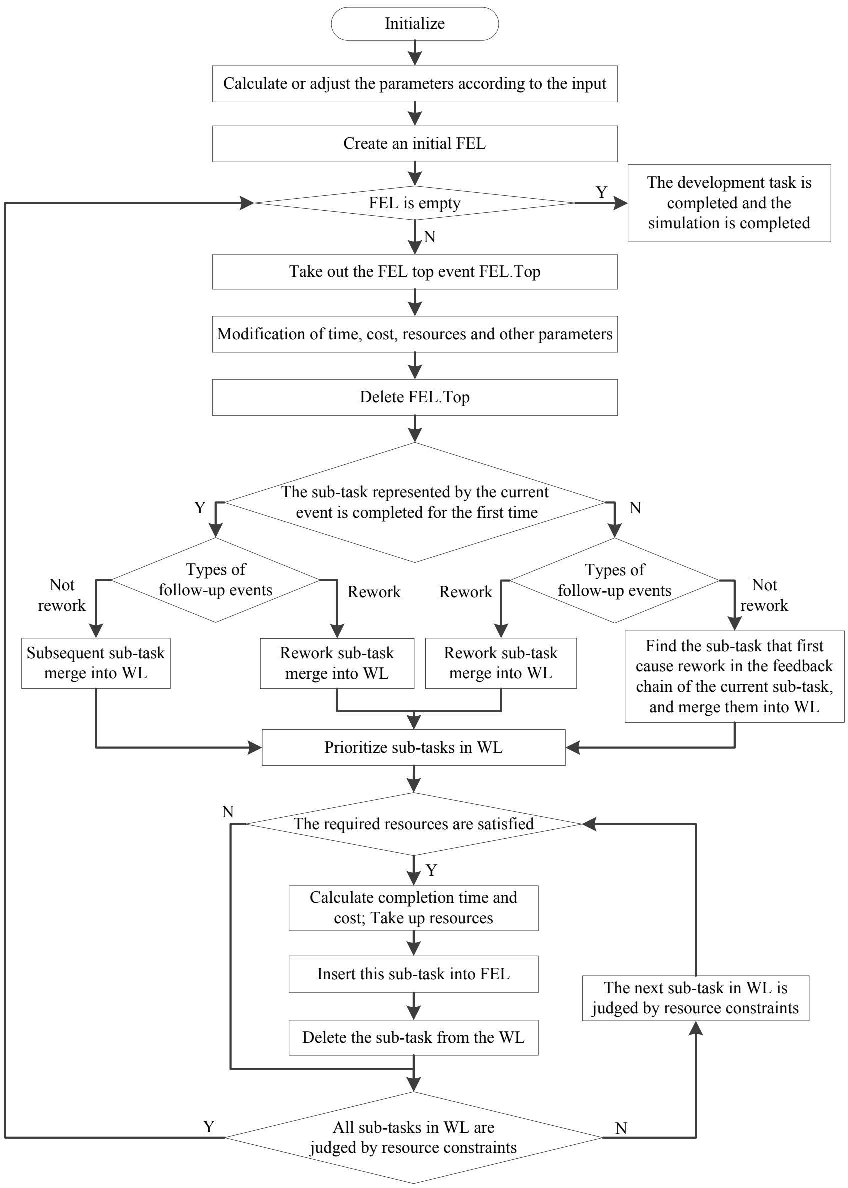

Figure 4. Single simulation operation flow chart.

Simulation allows the influence of the uncertainty and complexity of development tasks on the duration and cost of development tasks to be analyzed more intuitively and effectively [24,26]. The required input for the development task simulation model is the sub-task time, cost, required resources, DSM, FRP, FRI, HRP, and HRI. To establish the change of the trigger state of a sub-task at a given time point, the state includes the completion of each sub-task, execution, queuing, and so on.

5. Case Study on the Influence of Rework

5.1. Description of the Case Study

The development task of an uninhabited aerial vehicle (UAV) that includes 14 sub-tasks is used to conduct a case study. The duration and cost data of each sub-task are shown in Table 2. It is assumed that the duration and cost of each sub-task obey the triangular distribution. During each simulation run, the Monte Carlo method is used to extract the duration and cost of each sub-task. When calculating the rework parameters, O_DSM is derived according to EMDM and is normalized; then, the uncertainty degree and complexity degree of each sub-task are quantified according to the uncertainty influence factors and the complexity influence factors. Based on this, the PRP and PRI are calculated. If the effect of hidden rework is not considered, the DSM of the UAV development task is shown in Figure 5, and the FRP and FRI matrix are shown in Figure 6. When both foreseeable and hidden rework are considered, since the parameters of hidden rework cannot be predicted, the range of the hidden rework parameters can be set according to the degree of the uncertainty and complexity of the development task. In the corresponding value interval, parameters such as PHR, HRP, and HRI are generated randomly.

Table 2. The duration and cost data of each sub-task.

ID	Sub-Task Name	Duration (Days)			Cost (US$k)		
		D_o	D_m	D_p	C_o	C_m	C_p
1	Prepare Preliminary DR&O	1.9	2	3	8.6	9	13.5
2	Create Preliminary Design Configuration	4.75	5	8.75	5.3	5.63	9.84
3	Prepare Surfaced Models & Internal Drawings	2.66	2.8	4.2	3	3.15	4.73
4	Perform Aerodynamics Analyses & Evaluation	9	10	12.5	6.8	7.5	9.38
5	Create Initial Structural Geometry	14.3	15	26.3	128	135	236
6	Prepare Structural & Notes for FEM	9	10	11	10	11.3	12.4
7	Develop Freebody Diagrams & Applied Loads	7.2	8	10	11	12	15
8	Perform Weights & Inertia Analysis	4.75	5	8.75	8.9	9.38	16.4
9	Perform S&C Analyses & Evaluation	18	20	22	20	22.5	24.8
10	Develop Freebody Diagram & Applied Loads	9.5	10	17.5	21	22.5	39.4
11	Establish Internal Load Distributions	14.3	15	26.3	21	22.5	39.4
12	Evaluate Structural Strength, Stiffness, & Life	13.5	15	18.8	41	45	56.3
13	Preliminary Manufacturing Planning & Analyses	30	32.5	36	214	232	257
14	Prepare UAV Proposal	4.5	5	6.25	20	22.5	28.1

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1														
2	1								1					
3		1		1										
4	1		1											
5	1		1			1		1				.8	1	
6	1				.8									
7	1					.8								
8						1						1		
9	1		1	1				1						
10				1		1	1	1			1			
11						1	1	1		.9				
12	1					1	1			.9	.6			
13	1				1							1		
14	1	1	1	1	1	1	1	1	1	1	1	1	1	

Figure 5. Design structure matrix (DSM) of the development task.

ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1														
2	.4/.5								.2/.1					
3		.5/.3		.4/.5										
4	.3/.4		.5/.8											
5	.4/.1		.5/.1			.1/.1		.1/.1				.3/.3	.1/.1	
6	.1/.1				.4/.3									
7	.4/.5					.4/.8								
8						.5/.5						.5/.5		
9	.4/.3		.5/.3	.5/.3				.5/.3						
10				.1/.1		.5/.5	.2/.4	.1/.3			.4/.3			
11						.5/.5	.5/.5	.5/.3		.5/.3				
12	.4/.5					.4/.3	.5/.5			.5/.5	.4/.5			
13	.5/.9				.5/.9							.4/.3		
14	.3/.5	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	.4/.8	

Figure 6. Foreseeable rework probability (FRP) and foreseeable rework impact (FRI) matrix.

5.2. Effect of Rework Type on Duration and Cost

The analysis of the impact of rework on the duration and cost of the equipment development task is divided into two kinds of situations: those considering only the impact of foreseeable rework and those considering the effects of both foreseeable and hidden rework.

When only the impact of foreseeable rework on the duration and cost of the development task is considered, the rework parameters include the DSM, the FRP, and the FRI. At this time, parameters such as FRP and FRI are taken as constant values. When the effects of foreseeable rework and hidden rework on the duration and cost of the development task are considered, the rework parameters include the DSM, FRP matrix, FRI matrix, PHR matrix, HRP matrix, and HRI matrix. At this point, the foreseeable rework parameters are the same as in the previous case, and the hidden rework parameters are randomly generated.

When taking a specific random generation range for hidden rework parameters such as PHR, HRP, and HRI, the duration and cost are obtained through development task simulation. Then, the duration and cost are compared without considering hidden rework. The parameters of the hidden rework are as follows: the upper limit of PHR is 0.2, the upper limit of HRP is 0.2, and the upper limit of HRI is 0.2. We generated 5000 simulations for development tasks when considering only the foreseeable rework (without considering the hidden rework) and for comprehensively considering the foreseeable and hidden rework. The frequency histogram of the duration and cost of the development task for both cases is shown in Figure 7. In Figure 7a, the blue histogram represents the distribution of the development task duration without considering the hidden rework, and the red histogram represents the distribution of the development task duration when considering the hidden rework. In Figure 7b, the blue histogram represents the distribution of the development task cost without considering the hidden rework, and the red histogram represents the distribution of the development task cost when considering the hidden rework. The cumulative frequency curve of the development task duration and cost in both cases is shown in Figure 8. In Figure 8a, the blue curve represents the cumulative curve of the development task duration without considering the hidden rework, and the red curve represents the cumulative curve of the development task duration when considering the hidden rework. In Figure 8b, the blue curve represents the cumulative curve of the development task cost without considering the hidden rework, and the red curve represents the cumulative curve of the development task cost when considering the hidden rework.

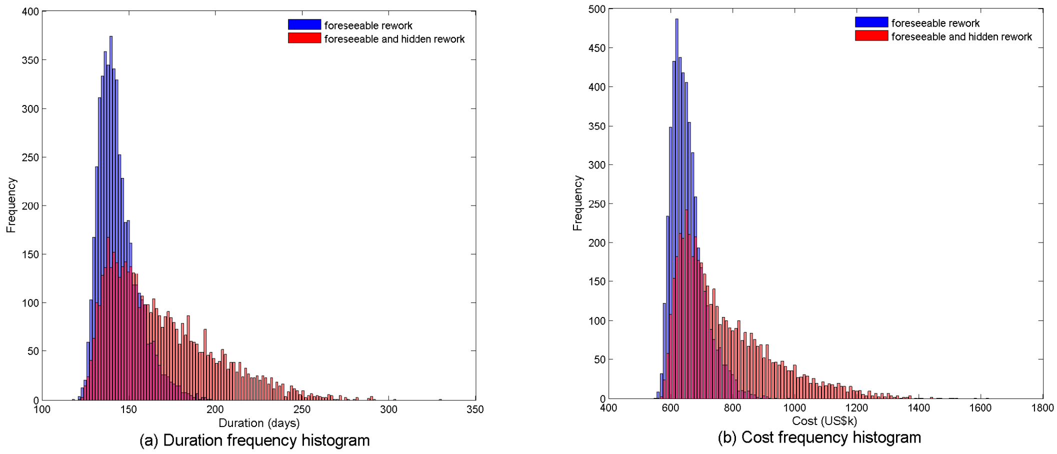

Figure 7. Duration, cost frequency histogram.

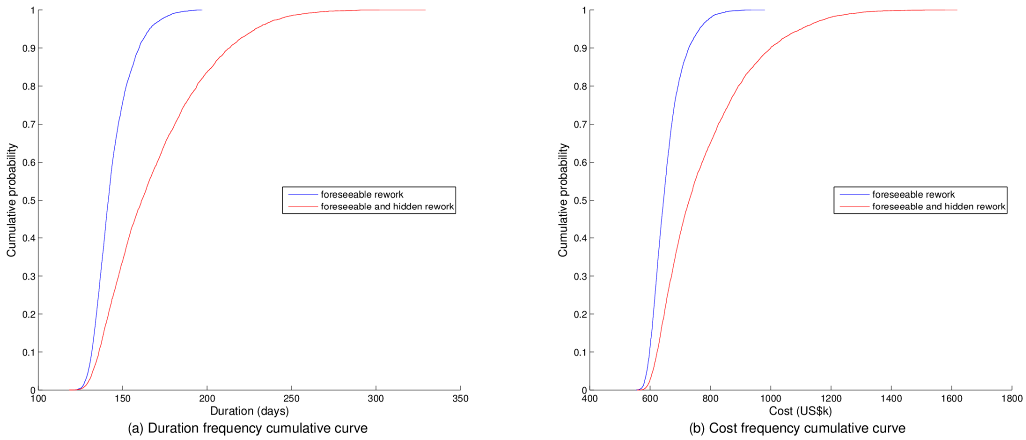

Figure 8. Duration, cost frequency cumulative curve.

The analysis shows that the average duration and cost of the development task are greater, the fluctuation range is wider, and the distribution is more dispersed when both the foreseeable rework and hidden rework are considered than when only the foreseeable rework is considered. The number of sub-tasks, ARP, ARI, and other parameters for a development task where the hidden rework effect is considered may increase because of the existence of the hidden rework. Therefore, the average duration is longer and the average cost is greater when the hidden rework effect is considered than they are when hidden rework is excluded. Since the implicit rework parameters cannot be accurately estimated, the uncertainty of parameters such as PHR, HRP, and HRI is greater. As a result, the fluctuation range of parameters such as the proportion of sub-tasks that may need rework, ARP, and ARI will increase. Therefore, when the implicit rework is not considered, the development task duration and cost fluctuation ranges are relatively small, and the distribution is relatively concentrated. When implicit rework is considered, the duration of the development task and the cost fluctuation range are relatively large, and the distribution is relatively decentralized.

5.3. Impact of Hidden Rework Parameters on Duration and Cost

To analyze the influence of different hidden rework parameters on the development schedule and cost, hidden rework parameters such as PHR, HRP, and HRI were taken from different ranges of random numbers. We compare the duration and cost of the development task under various conditions and analyze the influence of hidden rework on the duration and cost of the development task. The range of random number generation for PHR has a lower limit of 0 and an upper limit of 0.05, 0.1, . . . , 0.4, respectively. The range of random number generation for HRP has a lower limit of 0 and an upper limit of 0.05, 0.1, . . . , 0.5, respectively. The range of random number generation for HRI has a lower limit of 0 and an upper limit of 0.05, 0.1, . . . , 0.9, respectively. Simulation is carried out under the conditions of the upper limit of the implicit rework parameters, and the duration and cost of the development tasks under different parameters can be obtained.

The relationships between PHR, HRP, HRI, and the equipment development task duration are shown in Figure 9 based on the simulation data. Axis X indicates the upper limit of HRI, axis Y indicates the upper limit of HRP, and axis Z indicates the development task duration. The four surfaces from the bottom to the top are the duration surfaces of the development task when the upper limit of PHR is 0.1, 0.2, 0.3, and 0.4, respectively. The relationships between PHR, HRP, HRI, and the equipment development task cost are shown in Figure 10. Axis X indicates the upper limit of HRI, axis Y indicates the upper limit of HRP, and axis Z indicates the development task cost. The four surfaces from the bottom to the top are the cost surfaces of the development task when the upper limit of PHR is 0.1, 0.2, 0.3, and 0.4, respectively.

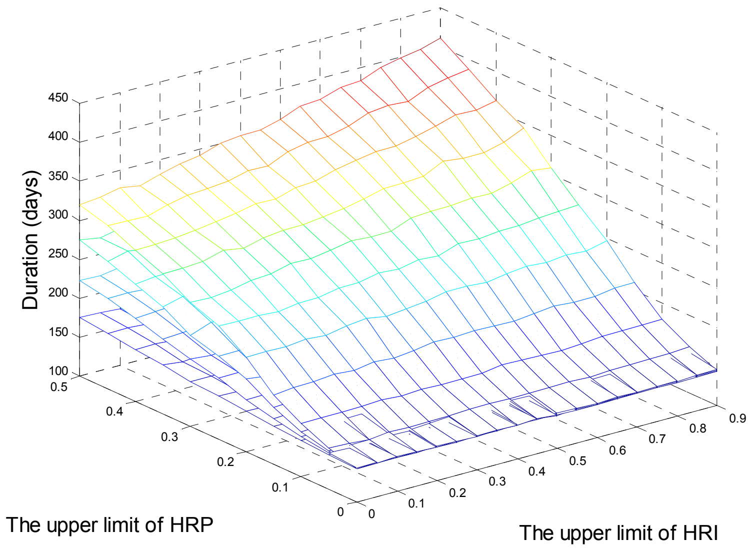

Figure 9. Relationships between rework parameters and duration.

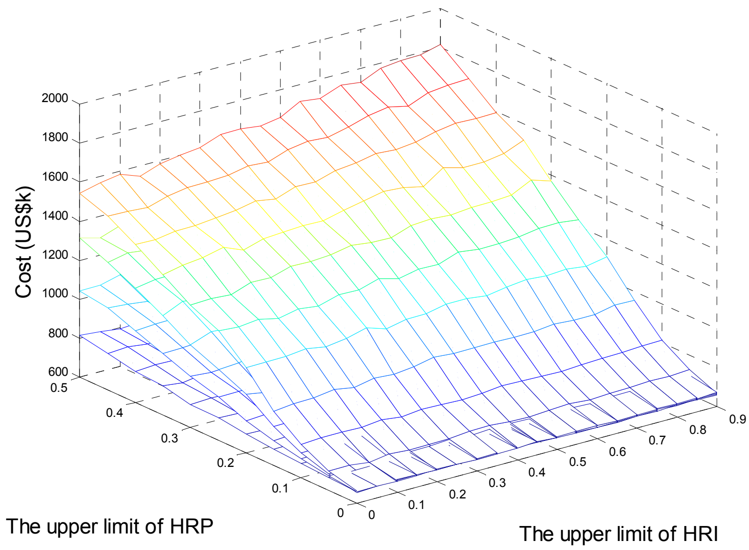

Figure 10. Relationships between rework parameters and cost.

The duration and cost of the equipment development task will increase with PHR, HRP, and HRI. Among these, PHR and HRP have a greater impact on development task duration and cost.

The relationships between equipment development duration, cost, and PHR when the upper limit of HRP is 0.2 and the upper limit of HRI is 0.2 are shown in Figure 11. As PHR increases, the number of sub-tasks occurring during the execution of an equipment development task will increase, and its duration and cost will increase. As PHR increases, the duration and cost of equipment development increase as well.

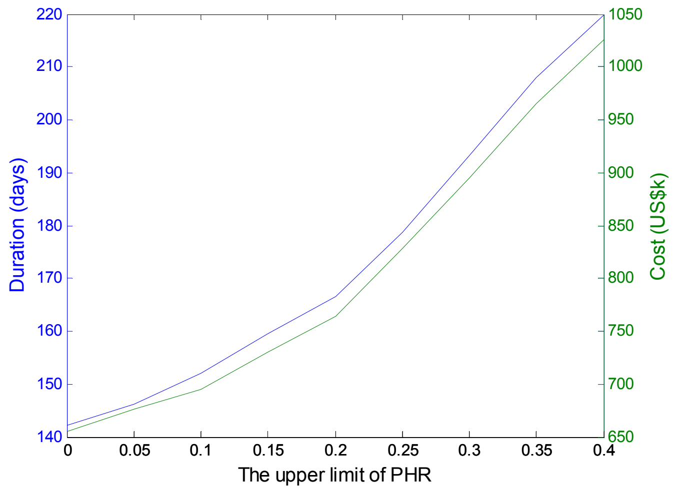

Figure 11. Relationships between duration, cost, and proportion of sub-tasks that may contain hidden rework (PHR).

During an equipment development task, ARP will increase as HRP increases. This increases the number of rework sub-tasks where rework must occur as well as the duration and cost of the overall equipment development task. The rate of increase is roughly proportional to HRP and is rapid.

When HRI increases, the number of implicit rework sub-tasks does not change, but the impact of these hidden rework sub-tasks increases, and the rework workload increases correspondingly. The duration and cost of equipment development will also increase, at a rate roughly proportional to the probability of implied rework, but it will be smaller than in the other two cases.

6. Conclusions and Outlook

This study divides rework in equipment development tasks into foreseeable and hidden types according to their characteristics, defines the concepts of foreseeable rework and hidden rework, and uses several methods to express the parameters of the two types. Unlike the traditional representation (which considers only foreseeable rework), the representation in this study can describe the actual situation of rework in a development task realistically.

This study analyzes the influencing factors of rework, establishes mapping and mathematical models of the main influencing factors in rework and rework parameters, and quantifies the rework parameters according to the model. The resulting rework parameter quantification model considers the influence of factors such as the degree of dependency between sub-tasks, uncertainty, and complexity, making it more scientific than previous models.

Based on the classification and description of rework and the quantification of rework parameters, this study quantitative analyzes the influence of rework types and parameters on the duration and cost of equipment development tasks by doing a simulation that reflects the operation effects of development tasks more accurately and analyzes the influence of rework on development tasks more deeply.

The results show that the mean duration and cost of a development task is greater, the range of volatility is wider, and the distribution is more dispersed when both foreseeable and hidden rework are considered than when only predictable rework is considered. In other words, the existence of hidden rework increases the duration and cost of a development task and widens their fluctuation range. The duration and cost of an equipment development task will increase with an increase in PHR, HRP, and HRI. Of these, PHR and HRP will have greater impacts. The PHR, HRP, and HRI parameters increase with an increase in development task uncertainty and complexity. Therefore, duration and cost will increase along with an increase in development task uncertainty and complexity.

Future studies could further explore quantitative determination methods for rework parameters. The quantification of rework parameters is an important basic factor in research on equipment development tasks. This study considers just two main factors affecting the rework of a development task—uncertainty and complexity. It is necessary to refine the factors that influence rework parameters, combine relevant theoretical analyses, mine historical data on development tasks, and construct a more effective method of quantifying rework parameters. In addition, methods of classifying development task reworking and of representing rework parameters should be explored in depth to enable the construction of a more complete description model for development task rework.

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References

1. Rao, R.; Zhang, X.P.; Shi, Z.P.; Luo, K.Y.; Tan, Z.F.; Feng, Y.F. A systematical framework of schedule risk management for power grid engineering projects' sustainable development. *Sustainability* **2014**, *6*, 6872–6901. [CrossRef]
2. Chen, T. Competitive and sustainable manufacturing in the age of globalization. *Sustainability* **2016**, *9*, 26. [CrossRef]
3. Kasm, O.A.; Yassine, A. Product development network modelling extensions to the cycle elimination method. *Comput. Ind. Eng.* **2018**, *119*, 321–337. [CrossRef]
4. Wynn, D.C.; Eckert, C.M. Perspectives on iteration in design and development. *Res. Eng. Des.* **2017**, *28*, 153–184. [CrossRef]
5. Meier, C.; Browning, T.R.; Yassine, A.A.; Walter, U. The cost of speed: Work policies for crashing and overlapping in product development projects. *IEEE T. Eng. Manag.* **2015**, *62*, 237–255. [CrossRef]
6. Browning, T.R. Applying the design structure matrix to system decomposition and integration problems: A review and new directions. *IEEE T. Eng. Manage.* **2001**, *48*, 292–306. [CrossRef]
7. Browning, T.R. Design structure matrix extensions and innovations: A survey and new opportunities. *IEEE Trans. Eng. Manag.* **2016**, *63*, 27–52. [CrossRef]
8. Yassine, A.A.; Whitney, D.E.; Zambito, T. Assessment of rework probabilities for simulating product development processes using the design structure matrix(DSM). In Proceedings of the ASME 2001 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Pittsburgh, Pennsylvania, 9–12 September 2001; pp. 1–9.
9. Steward, D.V. The design structure system: A method for managing the design of complex systems. *IEEE Trans. Eng. Manag.* **1981**, *3*, 71–74. [CrossRef]
10. Fang, C.; Marle, F. Dealing with project complexity by matrix-based propagation modelling for project risk analysis. *J. Eng. Des.* **2013**, *24*, 239–256. [CrossRef]
11. Yang, Q.; Zheng, L.; Kherbachi, S. Multi-domain integration of team-product-function and organization clustering in product development project. *Syst. Eng. Theory Pract.* **2018**, *38*, 1557–1565. (In Chinese)
12. Atkinson, R.; Crawford, L.; Ward, S. Fundamental uncertainties in projects and the scope of project management. *Int. J. Proj. Manag.* **2006**, *24*, 687–698. [CrossRef]
13. Little, T. Context-adaptive agility: Managing complexity and uncertainty. *IEEE Softw.* **2005**, *22*, 28–35. [CrossRef]

14. Meyer, A.D.; Loch, C.H.; Pich, M.T. Managing project uncertainty: From variation to chaos. *IEEE Eng. Manag. Rev.* **2002**, *30*, 60–67. [CrossRef]
15. Jensen, C.; Johansson, S.; Löfström, M. Project relationships–A model for analyzing interactional uncertainty. *Int. J. Proj. Manag.* **2006**, *24*, 4–12. [CrossRef]
16. Li, W.L.; Moon, Y.B. Modeling and managing engineering changes in a complex product development process. *Int. J. Adv. Manuf. Technol.* **2012**, *63*, 863–874. [CrossRef]
17. Yang, Q.; Lu, T.; Yao, T.; Zhang, B. The impact of uncertainty and ambiguity related to iteration and overlapping on schedule of product development projects. *Int. J. Proj. Manag.* **2014**, *32*, 827–837. [CrossRef]
18. Zhang, Y.L.; Yang, N.D. Literature review on definition of concept, analysis of characteristics, identification of types and measure methods of project complexity. *Manag. Rev.* **2013**, *25*, 133–141. (In Chinese)
19. Zheng, Y.J.; Yang, Y.; Zhang, N.; Jiao, B. A supernetwork-based model for design processes of complex mechanical products. *Sustainability* **2016**, *8*, 992. [CrossRef]
20. Baccarini, D. The concept of project complexity—A review. *Int. J. Proj. Manag.* **1996**, *14*, 201–204. [CrossRef]
21. Lu, Y.B.; Luo, L.; Wang, H.L.; Le, Y.; Shi, Q. Measurement model of project complexity for large-scale projects from task and organization perspective. *Int. J. Proj. Manag.* **2015**, *33*, 610–622. [CrossRef]
22. Bosch-Rekveldt, M.; Jongkind, Y.; Mooi, H.; Bakker, H.; Verbraeck, A. Grasping project complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework. *Int. J. Proj. Manag.* **2011**, *29*, 728–739. [CrossRef]
23. Rebentisch, E.; Schuh, G.; Riesener, M.; Breunig, S.; Pott, A.; Sinha, K. Assessment of changes in technical systems and their effects on cost and duration based on structural complexity. *Procedia Cirp* **2016**, *55*, 35–40. [CrossRef]
24. Browning, T.R.; Eppinger, S.D. Modeling impacts of process architecture on cost and schedule risk in product development. *IEEE Trans. Eng. Manag.* **2002**, *49*, 428–442. [CrossRef]
25. Abdelsalam, H.M.; Rasmy, M.H.; Mohamed, H.G. A simulation-based time reduction approach for resource constrained design structure matrix. *Int. J. Model. Optim.* **2014**, *4*, 51–55. [CrossRef]
26. Cho, S.H.; Eppinger, S.D. A simulation-based process model for managing complex design projects. *IEEE Trans. Eng. Manag.* **2005**, *52*, 316–328. [CrossRef]
27. Zhang, X.L.; Tan, Y.J.; Yang, Z.W. Simulation modeling of high-end equipment development task influenced by multiple uncertainty factors. *Syst. Eng. Theory Pract.* **2018**, *40*, 1265–1273. (In Chinese)
28. Luo, J.X. A simulation-based method to evaluate the impact of product architecture on product evolvability. *Res. Eng. Des.* **2015**, *26*, 355–371. [CrossRef]
29. Karniel, A.; Reich, Y. Multi-level modelling and simulation of new product development processes. *J. Eng. Des.* **2013**, *24*, 185–210. [CrossRef]
30. Maier, J.F.; Wynn, D.C.; Biedermann, W.; Lindemann, U.; Clarkson, P.J. Simulating progressive iteration, rework and change propagation to prioritise design tasks. *Res. Eng. Des.* **2014**, *25*, 283–307. [CrossRef]
31. Thiry, M. Sensemaking in value management practice. *Int. J. Proj. Manag.* **2001**, *19*, 71–77. [CrossRef]
32. Rosen, M.A.; Kishawy, H.A. Sustainable manufacturing and design: Concepts, practices and needs. *Sustainability* **2012**, *4*, 154–174. [CrossRef]
33. Galal, N.; Moneim, A. A mathematical programming approach to the optimal sustainable product mix for the process industry. *Sustainability* **2015**, *7*, 13085–13103. [CrossRef]