sustainability

MDPI

Article

Skeleton and Infill Housing Construction Delivery Process Optimization Based on the Design Structure Matrix

Xinying Cao [1], Xiaodong Li [2,*], Yangzhi Yan [3] and Xiang Yuan [1]

[1] School of Civil Engineering, Department of Construction Management, Hainan University, Haikou 570228, China; cxynews@outlook.com (X.C.); 17766959635@163.com (X.Y.)

[2] School of Civil Engineering, Department of Construction Management, Tsinghua University, Beijing 100084, China

[3] Department of Construction Management, School of Construction Management and Real Estate, Chongqing University, Chongqing 400044, China; xiaoqie.good@163.com

* Correspondence: eastdawn@tsinghua.edu.cn; Tel.: +86-10-62784957

Received: 5 November 2018; Accepted: 29 November 2018; Published: 3 December 2018

check for updates

Abstract: Skeleton and Infill (SI) housing system is considered as a significant path of sustainably prolonging building life by improving structural durability and infill variability for its nature that the skeleton system is fixed, while the infill system could be rebuilt to satisfy users' changing demands in different stage without damaging the skeleton system. The application of a SI housing system involves two new characteristics compared to traditional cast-in-place housing system: components production in factories and site construction are carried out simultaneously; the skeleton system and the infill system are constructed in parallel phases, which increase enormous parallel work. Iterations and rework would increase with the improper handling of parallel works, which lead to higher construction cost and lower participant willingness of stakeholders in SI housing construction delivery process. It is essential to establish a model to clarify the dependencies among major parallel work items and recognize parallel work sets to optimize the construction sequence for stakeholders to strengthen communication and coordination on key work items in a more efficiency way. By conducting investigations into the construction delivery process of typical SI housing projects in China, this paper developed a parallel collaborative mode based on the design structure matrix (DSM) to identify the complex dependencies among major cooperative work items. Furthermore, to provide an optimized parallel collaborative process, graph theory was introduced to find parallel work sets and eliminate repetition and iteration caused by improper work execution sequences. The results provide a guide for stakeholders to make appropriate cooperation strategies in implementing major work items and promoting cooperating efficiency by reducing iteration and rework.

Keywords: SI housing system; DSM; parallel collaborative process; stakeholders; graph theory

1. Introduction

Countries around the world were faced with varying degrees of housing shortage problems after World War II [1]. At the moment of rapid housing re-building, short delivery time, control of building process, narrow and clear specialized job, as well as avoiding complexity were considered as the main issues of building strategy [2], thus a large number of standardized and unified buildings were set up to meet the quantity requirement. In the mid-70s, when the number of houses surpassed the number of households, a shift occurred from focusing on quantity to quality [3]. A large number of standardized and unified housing are facing the predicament of fixed internal layouts greatly limiting users' abilities to reflect their own style and reconstruct their homes during different stages of housing life. Therefore, the fixed buildings face the eventuality of being demolished or destructive modification, despite the fact that their service life is far less than the design life [4], resulting in an enormous waste of resources and a series of environmental problems [5].

1.1. Definition of SI Housing

According to the need for flexibility and adaptability, housings have been segmented according to main building parts: load-bearing system, facade, interior walls and supply systems. That was the first transition from "closed" concrete "cast-in-site structure" where components rely on each other by mixed functions and fixed connections to "open" prefabrication through detachment and independence of different systems and components [6]. In 1961, N. John Habraken originated SI housing system that consists of mutual independent Skeleton (S) system and Infill (I) system derivate from open building theory [7]. In an SI housing system, housing structure is divided into the skeleton (S) part and infill (I) part based on the different functions and service life of the components, and connections are established between the two parts during the construction delivery process. The S part mainly contains the primary structure: beams, slabs, columns and bearing walls, and reparable parts in public sector, such as a public pipelines system, the exterior coating, and elevator equipment. The I part comprises removable parts according to housing quality: nonbearing walls and indoor pipelines, and parts used according to user demand, such as interior decorations and integrated kitchen/bathrooms [4]. The diagrammatic sketch of SI housing system is shown in Figure 1. The S part is fixed, while the I part could be rebuilt to satisfy updated functional demands during the service life of a SI housing, which greatly improves the variability and flexibility of building layouts. It was considered a new path for sustainably prolonging building life by improving structural durability and infill variability [8].

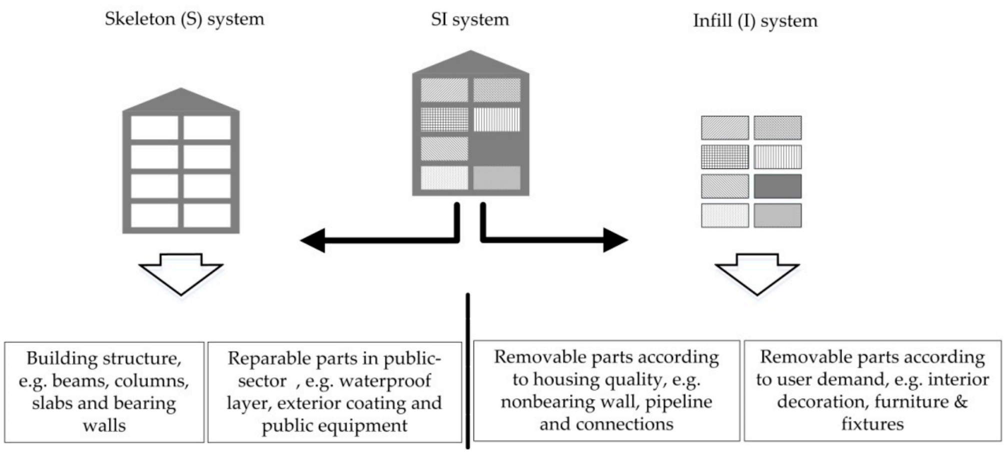

Figure 1. The diagrammatic sketch of SI housing system [4].

The SI housing system has been extensively used in many countries to provide a building fit to current and future users in a way that allows them to carry out the diverse activities required [9,10]. In the Netherlands, architecture research called SAR (Stichiting Architecture Research) was funded to specialize in skeleton and infill theory, led by Habraken, which has greatly facilitated the development of the SI housing system [11]. In 1975, Habraken worked for the department of architecture at MIT (Massachusetts Institute of Technology) and promoted the skeleton and infill theory in public housing maintenance and renovation. Hereafter, the Open House International (OHI) was founded to diffuse the skeleton and infill theory, to promote sustainable housing development in more countries [12]. In the last decade, the SI system has been successfully disseminating into industry and become recognizable by almost all in the Japanese industry [3] and has demonstrated advantages in both extending the housing service life through the necessary regular maintenance on skeleton parts, and meeting users' rising demands for diversification in housing layouts through flexible functional changes in the infill parts [13].

1.2. Dilemmas of SI Housing

With the rising demand to achieve a resource-conscious and environmentally friendly society in China, there has been an increasing interest in the sustainability of buildings [14]. In 2006, the SI housing system was introduced in China's building industry to help improve housing sustainability, due to its potential for promoting residential adaptability and flexibility. By learning from Japan and other countries where the SI housing system has already been widely used for years, the Chinese government developed a CSI (Chinese skeleton and infill) housing system to adapt Chinese housing needs. In support of the development of the CSI housing system, the Ministry of Housing and Urban-Rural Development of China (MOHURD) issued the CSI residential construction technical guidance document in October 2010 as a guideline to the CSI housing system at a national level [15]. Although the advantages of the SI housing system have been proven by its successful application in some countries, its uptake in China's building industry remains sluggish. Only a few research institutes and housing developers in China are interested in the research on the SI housing system, and most research works are confined to theoretical studies on a technology research [16–18] and development level [19–21]. Those studies largely demonstrate the practical technology methods and the effectiveness of SI housing in meeting users' changeable demands within China's housing industry. However, studies on management methods and stakeholder cooperation in the SI housing system are insufficient.

In the traditional cast-in-site construction mode in China, only developers, designers and contractors are the major players in the building construction process. Designers complete engineering drawings and blueprints according to developers' requirements and deliver them to contractors to implement the building and realize its complex functional requirements. In this process, developers, designers and contractors perform their duties in strict accordance with their respective mandates. The collaborative process among the three major players is relatively simple. Compared to traditional housing delivery process, the application of a SI housing system involves two new characteristics: components production in factories and site construction are carried out simultaneously; the S part and the I part are constructed in parallel phases, which increase enormous parallel works. Iterations and rework would increase with the improper handling of parallel works, which lead to higher construction cost and lower participant willingness of stakeholders in SI housing construction delivery process. SI housing formation heavily relies on integration of more complicated technologies and involves more interactive procedures, including extensive planning, components customization and manufacturing, and S part and I part connections. Moreover, researchers, manufacturers and suppliers are considered as important as developers, designers and contractors for implementing an SI housing project. As the stakeholders increase, the demand for communication and coordination among different stakeholders is consequently augmented. The SI housing system encourages cooperation among different stakeholders, not only in design phase, but also in the components production and supply phase and construction and assembly phase. The SI housing system is witnessing an increasing demand for cooperation and coordination among different professions, leading to a synergy of design integration, construction processes, and supply chain management in order to fully achieve optimal results. Therefore, the traditional cooperation mode cannot be directly transferred to the SI housing construction delivery process. It is necessary to establish a new collaborative process and optimize the coupling works and iterations among the stakeholders to increase project delivery efficiency and further to take full advantage of the SI housing system.

In this research, two key points are explored: (1) defining the major cooperative work items of different stakeholders and recognizing the complex dependencies and inner logical relationships among them; (2) identifying parallel work sets to optimize the execution sequences by reducing repetition and iteration and to promote collaborative efficiency.

2. Methodology

The design structure matrix (DSM), which is also called the dependency structure matrix (DSM), has been proven to be an effective method in visualizing information transfer among works and optimizing work scheduling [22]. In the DSM, the dependencies—including serial relationships, parallel relationships and iteration among work items in a complex project—are described using a mathematical matrix [23]. It can play a role in improving information transfer, decreasing rework and re-engineering [24,25]. DSM is proven to be an effective method in illustrating dependency relationships among buildings' product architecture. Schmidt, Deamer and Austin [26,27] proposed a DSM model with the capacity to compactly model a new buildings' product architecture, hence illustrating how well a proposed design can respond to change, through the clustering of modules and observing of dependency relationships in and outside a module. Schmidt, Deamer and Austin [28] applied DSM to identify all variant components to create a work breakdown structure and classify the components relationships. Schmidt, Vibaek and Austin [29] verified DSM could visualize the relationships between elements within a system and reveal about the capacity for an industrialized building to accommodate change, through clustering and impact analyses. In this paper, DSM is introduced to describe and optimize the dependencies of the main cooperative work items from different stakeholders, in order to reduce iteration and rework, so as to improve the collaborative efficiency and realize optimized resource configuration during the SI housing construction delivery process.

A DSM is a square matrix with identical row and column labels in which the diagonal represents the elements in row or column and the off-diagonal mark signifies the dependency of one element on another. The mark positioned in the lower left portion of the diagonal is the relationship or information provided by the element in the corresponding row to other elements in the column; the mark positioned in the upper right portion of the diagonal is the relationship or information that the element in the corresponding column depends on from other elements in the row. As illustrated in Figure 2, Element A provides something to Element D, and depends on something from Element B. Initially, the DSM is a binary DSM, also called a Boolean DSM [30,31], in which the relationship or information between elements can only be represented by two values, "0" and "1", or "×"and blank, as shown in Figure 2. In a Boolean DSM, the values can only indicate whether there is dependency between elements but cannot reflect the strength of the dependency. In order to overcome such a defect in the Boolean DSM, Smith and Eppinger [32] proposed the NDSM (numeric design structure matrix) based on the Boolean DSM and used specific digital quantification to describe the relationship or information strength of elements between rows and columns in the matrix. The schematic of the NDSM is shown in Figure 3.

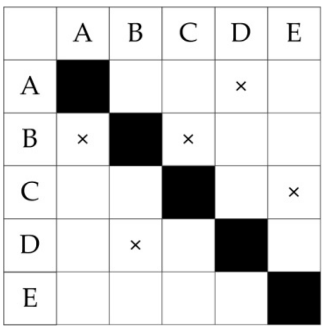

Figure 2. Schematic of the binary design structure matrix (DSM), or Boolean DSM.

	A	B	C	D	E
A		2		1	
B	2				
C				4	1
D			3		
E			2	3	

Figure 3. Schematic of the numeric design structure matrix (NDSM).

In the SI housing construction delivery process, a certain number of building components in both the S part and I part are manufactured in a factory using prefabrication technology [33]. This changes the working sequence from that in traditional housing construction, and brings many successor activities forward after foundation construction, resulting in increased parallel works and cross works for the SI housing construction delivery process. The increased parallel works and cross works are prone to increased rework at the risk of wasting of resources and additional cost, which brings a notable challenge to the working team of different stakeholders with different skills to for work together deliver a persuasive SI project. The DSM is introduced to find out the relationships among different works, breakdown the SI housing construction delivery process according to work categories, optimize parallel works and cross works, and finally recombine the work procedure in a more efficient way using matrix operations in order for the stakeholders to reduce conflict and improve productivity in the cooperation process, and thereby improve implementation efficiency. Browning [22] reviewed the application of DSMs in two main categories: static DSMs and dynamic DSMs including four distinct areas: component-based DSM, team-Based DSM, task-Based DSM and parameter-Based DSM. The taxonomy of DSMs is shown in Figure 4.

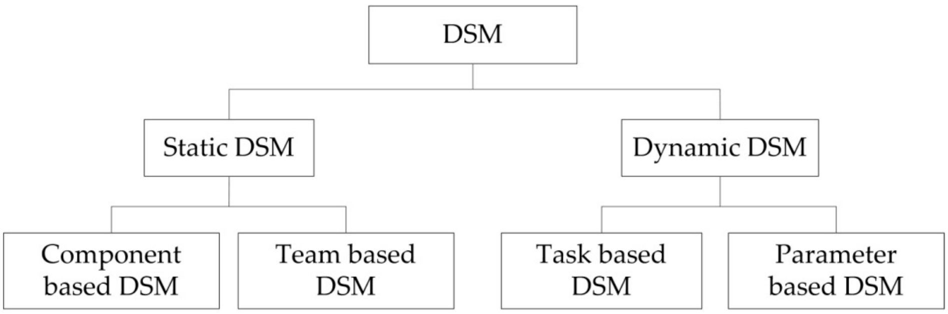

Figure 4. DSM taxonomy.

In a component-based DSM, the constituents of a system are expressed as the elements of rows and columns in the matrix, and the system is optimized by defining and studying the relationship between the sub-system and the constituents. In a team-based DSM, stakeholders of a system are considered the elements of rows and columns in the matrix, and the system is optimized by studying the relationship of information interactions among different stakeholders. In a task-based DSM, tasks of a system are regarded as the elements of rows and columns in the matrix, and the system is optimized by analyzing the relationship and information among tasks. In a parameter-based DSM, systematic parameters are considered as the elements of rows and columns in the matrix, and the system is optimized by analyzing the mutual relationship between systematic parameters.

This paper aimed to reduce the complexity and uncertainty of tasks in the SI housing construction delivery process and establish a more efficient work procedure for the stakeholders. Therefore, the task-based DSM was selected to identify the execution sequence and correlative dependence relationship between the main cooperative works, in order to decrease rework and unnecessary iterations, and thus optimize the SI housing construction delivery process.

3. Work Items and Dependency Identification in the SI Housing Construction Delivery Process

3.1. Decomposition of the SI Housing Construction Delivery Process

The total work of the SI housing system is divided into five sub-systems: the investment and development system, research and design system, production and supply system, construction and assembly system, and operation and management system, according to the normal process of housing and the specific features of SI housing. The five sub-systems and the relationships among them are shown in Figure 5.

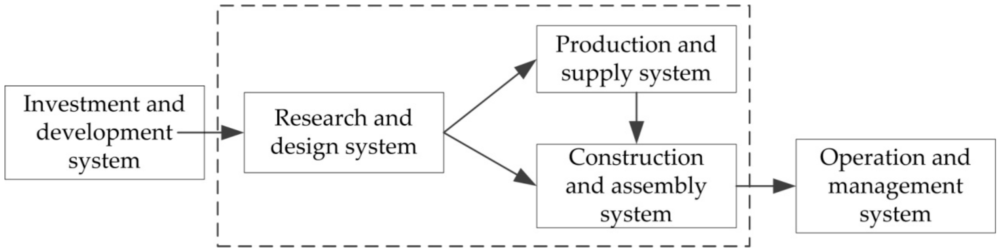

Figure 5. Sub-systems of SI housing.

Considering that the work in the investment and development system is more partial to the enterprise of strategic decision-making, it is generally implemented only by the participant-investor, rather than specific construction works cooperated on by several stakeholders from different fields. Similarly, the works in SI housing operations and the management stage are implemented by the property management company, and other stakeholders, such as designers, contractors, and material/equipment manufacturers and suppliers rarely participate in this stage. The main purpose of this paper is to explore an optimized implementation procedure for different stakeholders to promote collaborative efficiency during the SI housing delivery process; therefore, the research scope is confined to the research and design system, production and supply system, and construction and assembly system (hereinafter referred to as the three major sub-systems).

Twenty-eight semi-structured interviews with researchers, designers, housing developers, contractors, material/equipment manufacturers, and suppliers that participate in the SI housing construction delivery process (eight with researchers, five with designers, five with developers, four with contractors, and six with manufacturers/suppliers) were conducted to develop an in-depth understanding of the three major sub-systems. Most of interviewees participated in the SI demonstration projects in Beijing and Shanghai, which are the most representative SI projects so far in China. Overall, the average work experience length related to the SI housing system of the interviewees was 2.3 years. Details are listed in Table 1.

Table 1. Profiles of interviewees.

Job Category	Amount of Interviewees	Average Working Experience in Construction Industry			Average Working Experience in SI Housing System (Years)
		<5 Years	5–10 Years	>10 Years	
Researchers	8	2	4	2	2.7
Designers	5	2	2	1	2.2
Developers	5	2	2	1	2.0
Contractors	4	0	2	2	1.5
Manufacturers/suppliers	6	2	3	1	2.5
Total	28	8	13	7	2.3

Finally, 11 main work items that cover the three major sub-systems were elicited by scrutinizing the processes through which the SI housing system was adopted and utilized in residential projects by the interviewees. The 11 main work items are shown in Figure 6.

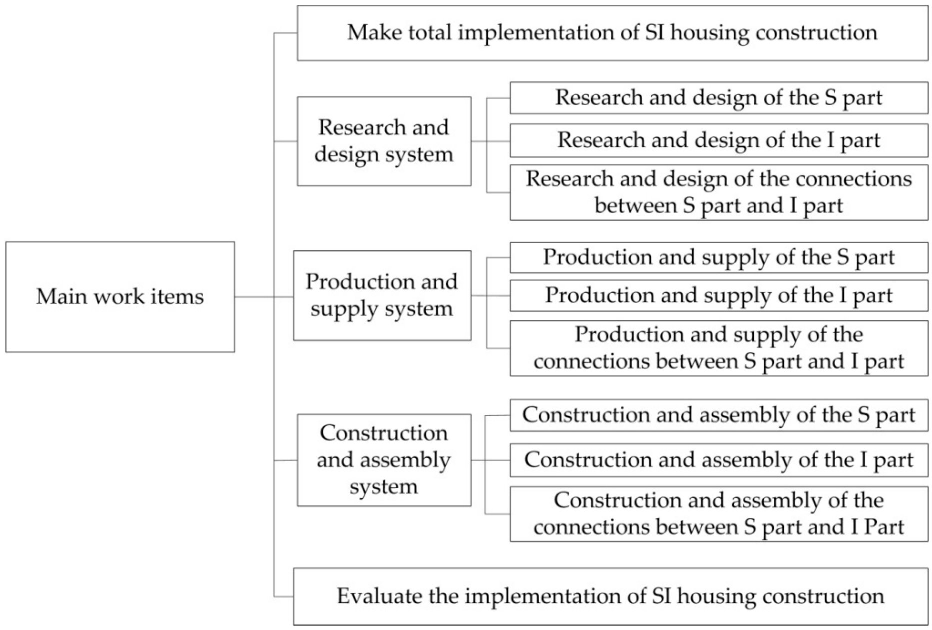

Figure 6. Main work items of the three major sub-systems.

3.2. Identification of the Relationships Among the Main Work Items

Sharman and Yassine [34] divided the relationships of the elements between ranks and lines in the NDSM into four categories: spatial linkage, energy linkage, information linkage and material linkage.

Four quadrants were used to refer to the four linkages between elements: The first quadrant is the spatial linkage; the second quadrant is the energy linkage; the third quadrant is the information linkage, and the fourth quadrant is the material linkage, as shown in Figure 7.

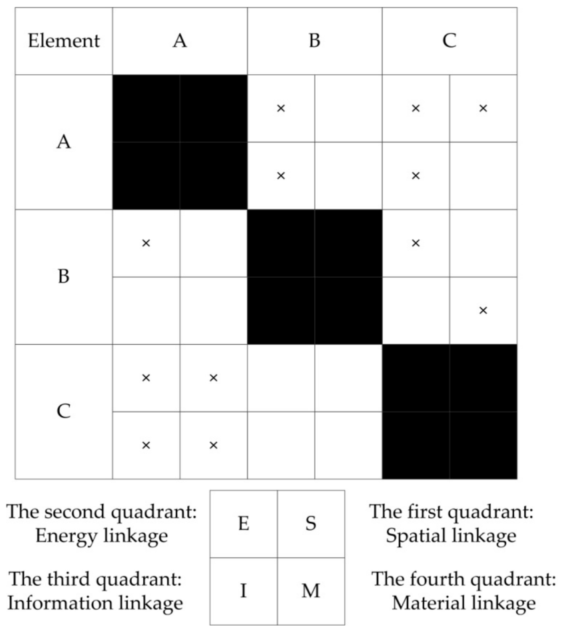

Figure 7. The implementation of the four quadrants in the NDSM.

Tang, Qian and Liu [35] used a four-point scale to express the relationship strength of corresponding linkages between elements on a scale from 0 to 3, where "3" represents "high degree of contact", "2" represents "middle degree of contact", "1" represents "low degree of contact", and "0" or blankness represents "no contact". Furthermore, a comprehensive weight method is introduced for dimensionality reduction of the four-vector matrix, as shown in Equation (1). The linkage strength in different quadrants is expressed by the product of the figure and its weight, and the sum of the products in the four quadrants represents the comprehensive relationship strength between the elements in corresponding rows and columns.

$$W_{ij} = \alpha S_{ij} + \beta E_{ij} + \gamma I_{ij} + \kappa M_{ij} \quad (1)$$

W_{ij}—the comprehensive relationship strength between the elements in row i and column j;
S_{ij}—the spatial linkage strength between the elements in row i and column j;
E_{ij}—the energy linkage strength between the elements in row i and column j;
I_{ij}—the information linkage strength between the elements in row i and column j;
M_{ij}—the material linkage strength between the elements in row i and column j;
α—the weight of spatial linkage strength in the comprehensive relationship strength;
β—the weight of energy linkage strength in the comprehensive relationship strength;
γ—the weight of information linkage strength in the comprehensive relationship strength;
κ—the weight of material linkage strength in the comprehensive relationship strength.

Twenty-eight semi-structured interviews with the stakeholders in Table 1 were conducted in an attempt to understand the weight of the four linkages and the relationship strength among the main work items. The results of interviews included the following:

(1) The weights of the four linkages are made equally important in the initial stage of SI housing development in China: $\alpha = \beta = \gamma = \kappa = 1$.
(2) The work item a_1 provides guidance and reference information for all subsequent work items, but subsequent work items exert no influence on a_1, thus the row of a_1 is full of different values that represent varying degrees of linkage strength with other elements, and all the column values of a_1 are 0. The work investments, marketing positioning, and product modeling that contribute to a_1 exert a direct influence on the work items a_2, a_3 and a_4 in the research and design system, the linkage strength values for a_2, a_3 and a_4 are higher than the values for a_5, a_6, a_7 in the production and supply system, and a_8, a_9, a_{10} in the construction and assembly system, respectively.
(3) The work item a_{11} refers to evaluation of the implementation and performance of the whole SI housing construction delivery process, to verify whether it realizes the initial target. All previous work items exert an influence on a_{11}, but a_{11} exerted no influence on previous work items, thus the column of a_{11} is full of different values that represent varying degrees of linkage strength with other elements, and all the row values of a_{11} are 0. Considering that the work items a_8, a_9, a_{10} in the construction and assembly system are the core steps of the whole SI housing construction delivery process and determine the final realization of SI housing, the linkage strength values with the three work items are higher than that with other items. The work items a_5, a_6, a_7 in the production and supply system define material and component production and manufacturing techniques, and have a superior influence on a_{11}. The work items a_2, a_3 and a_4 in the research and design system provide design guidance for SI housing construction, and exert no direct influence on a_{11}, thus the linkage strength values for a_2, a_3 and a_4 are smaller than that for other items.
(4) The information communication and feedback among a_2, a_3 and a_4 realize the design of the SI housing together. However, a_2 is superior to a_3 in space from the perspective of housing functions in the S part and I part, as well as the implemented subsequence. A suitable adjustment for a_2 could be conducted in accordance with feedback from a_3. The work items a_2 and a_3 determine the implementation of a_4 together. Simultaneously, subtle adjustments will be conducted in line

with the technical level and suitable conditions of a_4. The relationships among a_8, a_9, and a_{10} are similar to the relationships among a_2, a_3 and a_4.

(5) From the longitudinal angle of the cooperation process, a_2 determines the implementation of a_5 and a_8, and a_5 and a_8 interact with each other. The production and supply scheme of a_5 is adjusted in accordance with planning, schedule and site construction conditions, and construction and assembly planning of a_8 is adjusted in accordance with production schedules and supply situations of a_5 simultaneously. Moreover, conflicts and low feasibility in the implementation of a_5 and a_8 feed back to a_2, and a_2 is modified in line with the feedback information. The relationship among a_3, a_6 and a_9, as well as a_4, a_7 and a_{10}, respectively, is equal to the relationships among a_2, a_5 and a_8.

A comprehensive DSM of the main work items and the dependencies among them in the SI housing construction delivery process is established according to the results of interviews, as shown in Figure 8.

		a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
Make total implementation of SI housing construction	a_1		5	5	5	3	3	3	3	3	3	3
Research and design of the S part	a_2	0		6	6	6	0	0	6	0	0	2
Research and design of the I part	a_3	0	4		6	0	6	0	0	6	0	2
Research and design of the connections between S part and I part	a_4	0	2	2		0	0	6	0	0	6	2
Production and supply of the S part	a_5	0	1	0	0		0	0	4	0	0	4
Production and supply of the I part	a_6	0	0	1	0	0		0	0	4	0	4
Production and supply of the connections between S part and I part	a_7	0	0	0	1	0	0		0	0	4	4
Construction and assembly of the S part	a_8	0	1	0	0	3	0	0		6	6	6
Construction and assembly of the I part	a_9	0	0	1	0	0	3	0	4		6	6
Construction and assembly of the connections between S part and I part	a_{10}	0	0	0	1	0	0	3	2	2		6
Evaluate the performance of SI housing construction	a_{11}	0	0	0	0	0	0	0	0	0	0	

Figure 8. Comprehensive DSM of the major work items.

4. SI Housing Construction Delivery Process Optimization

4.1. Optimization Methods of the DSM

Liu, Hu and Li [36] divided the optimization methods of the DSM into three categories: optimization based on graph theory [37,38], optimization based on fuzzy relations [39,40], and optimization based on intelligent methods [41,42], as shown in Table 2. There are only 11 main work items in the DSM and identification and reconstitution of parallel contact in this research is low complexity, therefore optimization based on graph theory can acquire an exact solution within a reasonable time. For this reason, optimization based on graph theory is employed for the DSM operation in this research.

Table 2. Solution algorithm of the coupling contact set based on the DSM.

Optimization Methods	Feature
Optimization based on graph theory	Matrix operates using mature mathematical tools. This optimization method is generally applied to small or medium-sized projects.
Optimization based on fuzzy relations	This optimization method is generally applied to the optimization of a DSM based on fuzzy relations
Optimization based on intelligent methods	Matrix is optimized using a genetic algorithm or simulated annealing algorithm. This optimization method is generally applied to the optimization of complex, multi-objective and multi-constraint DSMs.

The essence of parallel contact identification is the process of searching for information circuits using graph theory. The graph is the set of knots and directed arcs linking the knots. A graph in this case is an ordered couple, marked as Graph $G = \langle V, E \rangle$, in which:

(1) $V = \{v_1, v_2 \cdots, v_n\}$ is a finite and nonempty set of knots, called the knots set. v_i is a knot.
(2) $E = \{e_{12}, e_{13}, \cdots, e_{ij}\}$ is a set of finite edges, called the edge set. e_{ij} is an edge.
(3) Element e_{ij} in E corresponds to the knot (v_i, v_j) in V.
(4) If there is an access from knot v_i to knot v_j, it is considered reachable between v_i and v_j. Graph G is considered a strongly connected graph when any knot is reachable by other knots in it [43].

Assuming that there is a certain order for knot v_i to knot v_n in V, the n-order matrix $A = (a_{ij})_{n\times n}$ is the adjacent matrix of G. The n-order matrix $P = (p_{ij})_{n\times n}$ is the reachable matrix of G, in which:

(1) i =1, 2, . . . , n; j =1, 2, . . . , n;
(2) If $(v_i, v_j) \in E$, a_{ij} = 1; otherwise a_{ij} = 0.
(3) If there is at least one non-zero access from v_i to v_j, p_{ij} = 1; otherwise p_{ij} = 0.

The relationship between matrix A and matrix P is shown in Equation (2).

$$P = A^{(1)} \vee A^{(2)} \vee \cdots \vee A^{(\mathrm{n})} = \bigvee_{j=1}^{n} A^{(i)} \quad (2)$$

where $A^{(\mathrm{n})}$ is the n-degree power matrix of A; $\vee$ is the "Boolean sum"; and $\wedge$ is the "Boolean product". The algorithms of the "Boolean sum" and "Boolean product" are shown in Table 3.

Table 3. Algorithms of $\vee$ and $\wedge$.

Algorithm of $\vee$	$\vee$	0	1	Algorithm of $\wedge$	$\wedge$	0	0
	0	0	1		0	0	0
	1	1	1		1	0	1

P^T is the transposed matrix of the reachable matrix P. The algorithm of $P \cap P^T$ is defined in Equation (3).

$$P \cap P^T = \begin{pmatrix} p_{11} & \cdots & p_{1n} \\ \vdots & \ddots & \vdots \\ p_{n1} & \cdots & p_{nn} \end{pmatrix} \cap \begin{pmatrix} p_{11} & \cdots & p_{n1} \\ \vdots & \ddots & \vdots \\ p_{1n} & \cdots & p_{nn} \end{pmatrix} = \begin{pmatrix} p_{11}^2 & \cdots & p_{1n} \cdot p_{n1} \\ \vdots & \ddots & \vdots \\ p_{n1} \cdot p_{1n} & \cdots & p_{nn}^2 \end{pmatrix} \quad (3)$$

If knot v_i is reachable from knot v_j in a graph, p_{ij} = 1; if it is reachable from v_j to v_i, p_{ji} = 1. Therefore, if and only if $p_{ij} \cdot p_{ji}$ = 1, can v_i and v_j be mutually reachable. According to the rule above, if a non-zero element in row i is in column $j_1, j_2, \cdots, j_k$ simultaneously, knots v_i, $v_{j1}, v_{j2}, \cdots, v_{jk}$ are on the same strongly connected branch, that is the sub-graph derived from $\{ v_i, v_{j1}, v_{j2}, \cdots, v_{jk}\}$ is a strongly connected component in Graph G [44].

4.2. Optimization Result of the DSM

The major operation of process optimization is conducting concurrent engineering structure identified coupling work sets and eliminating repetition and iterations caused by an improper work execution sequence, so as to promote executive efficiency. The rules of process optimization based on the DSM are described as follows:

- In the DSM, if all elements in one row are zero, it indicates that the work in this row will not output information to other works, thus it will be executed last.
- In the DSM, if all elements in one column are zero, it indicates that the work in this column has no need for inputting information from other activities, thus it will be executed at the beginning.
- The work items in a coupling work set mean that relationships among these works are close. Therefore, the work items in a coupling work set should operate as a single holistic work.

Work items should be divided by priority ranking first and reconstructed according to the priority ranking. The method for dividing priority ranking is described as follows:

- Coupling work sets in the reachable matrix P are normalized as single holistic works respectively. Matrix P' is the reduced matrix of matrix P after reducing the dimension of matrix P.
- $P'E_{m-1} = (p_1, p_2, \cdots, p_n)^T (m \geq 1)$; n-dimensional column vector $E_0 = (1, 1, \cdots, 1)^T$, $E_m = (e_1, e_2, \cdots, e_n)^T$; When $p_i \in \{0, 1\}$, $e_i = 0$; When $p_i \notin \{0,1\}$, $e_i = 1$. Therefore, the necessary and sufficient condition for work a_i to be an m-level element is $p_i = 1$.

In this research, the SI housing construction delivery process is considered as Graph G. The work items in the SI housing construction delivery process are knots V in G, and the relationships among work items are limited edge E in G, thus the Boolean DSM of the SI housing construction delivery process is the adjacent matrix A of G. According to this rule, coupling work identification in the SI housing construction delivery process is transferred into solving strongly connected components of the graph.

The DSM of the SI housing construction delivery process established in Section 3 is transferred into a Boolean DSM, as shown in Figure 9. Thus, its corresponding reachable matrix P can be obtained by the algorithm of Formula 2, as shown in Figure 10. The operation result of $P \cap P^T$ based on the algorithm of Formula 3 is show in Figure 11.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
a_1		1	1	1	1	1	1	1	1	1	1
a_2	0		1	1	1	0	0	1	0	0	1
a_3	0	1		1	0	1	0	0	1	0	1
a_4	0	1	1		0	0	1	0	0	1	1
a_5	0	1	0	0		0	0	1	0	0	1
a_6	0	0	1	0	0		0	0	1	0	1
a_7	0	0	0	1	0	0		0	0	1	1
a_8	0	1	0	0	1	0	0		1	1	1
a_9	0	0	1	0	0	1	0	1		1	1
a_{10}	0	0	0	1	0	0	1	1	1		1
a_{11}	0	0	0	0	0	0	0	0	0	0	

Figure 9. Boolean DSM of the SI housing construction delivery process.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
a_1		1	1	1	1	1	1	1	1	1	1
a_2	0		1	1	1	1	1	1	1	1	1
a_3	0	1		1	1	1	1	1	1	1	1
a_4	0	1	1		1	1	1	1	1	1	1
a_5	0	1	0	0		1	1	1	1	1	1
a_6	0	0	1	0	0		1	1	1	1	1
a_7	0	0	0	1	0	0		1	1	1	1
a_8	0	1	0	0	1	0	0		1	1	1
a_9	0	0	1	0	0	1	0	1		1	1
a_{10}	0	0	0	1	0	0	1	1	1		1
a_{11}	0	0	0	0	0	0	0	0	0	0	

Figure 10. Results of reachable matrix *P*.

	a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8	a_9	a_{10}	a_{11}
a_1		0	0	0	0	0	0	0	0	0	0
a_2	0		1	1	1	0	0	1	0	0	0
a_3	0	1		1	0	1	0	0	1	0	0
a_4	0	1	1		0	0	1	0	0	1	0
a_5	0	1	0	0		0	0	1	0	0	0
a_6	0	0	1	0	0		0	0	1	0	0
a_7	0	0	0	1	0	0		0	0	1	0
a_8	0	1	0	0	1	0	0		1	1	0
a_9	0	0	1	0	0	1	0	1		1	0
a_{10}	0	0	0	1	0	0	1	1	1		0
a_{11}	0	0	0	0	0	0	0	0	0	0	

Figure 11. Operation result of $P \cap P^T$.

According to the results of $P \cap P^T$ in Figure 11 and the algorithm of coupling work identification in Section 4.1, five parallel work sets of the SI housing construction delivery process are obtained, including {a_2, a_3, a_4}, {a_2, a_5, a_8}, {a_3, a_6, a_9}, {a_4, a_7, a_{10}} and {a_8, a_9 a_{10}}. Every coupling work set is marked with a bold wireframe in Figure 11. The method confirmed in Section 4.1 is applied to optimize the SI housing construction delivery process. The work items a_2, a_3, a_4 in the research and design system and a_8, a_9, a_{10} in the construction and assembly system belong to two coupling work sets, respectively. In the SI housing construction delivery process, the research and design system is prior to the construction and assembly system in the implementation sequence. Therefore, a_2, a_3, a_4 and a_8, a_9, a_{10} are normalized as a whole entirety during the parallel work sets normalizing operation. Finally, the reduced matrix P' of P is calculated and shown in Equation (4).

$$P' = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The method confirmed in Section 4.1 is applied to identify the work execution sequence. The operation process is shown in follows:

$$\begin{aligned} P'E_0 &= (7,6,5,4,3,2,1)^T, L_1 = \{a_{11}\} \\ P'E_1 &= (6,5,4,3,2,1,0)^T, L_2 = \{a_8, a_9, a_{10}\} \\ P'E_2 &= (5,4,3,2,1,0,0)^T, L_3 = \{a_7\} \\ P'E_3 &= (4,3,2,1,0,0,0)^T, L_4 = \{a_6\} \\ P'E_4 &= (3,2,1,0,0,0,0)^T, L_5 = \{a_5\} \\ P'E_5 &= (2,1,0,0,0,0,0)^T, L_6 = \{a_2, a_3, a_4\} \\ P'E_6 &= (1,0,0,0,0,0,0)^T, L_7 = \{a_1\} \end{aligned}$$

According to the work execution sequence above, as well as the dependencies among work items in practical projects, {a_2, a_5, a_8}, {a_3, a_6, a_9} and {a_4, a_7, a_{10}} are also considered new coupling work sets, which provides a guide for stakeholders to make intensive management program and appropriate cooperation strategies to reduce repetition and iteration in the implement of these parallel work sets.

5. Discussion

An optimized SI housing construction delivery process is established in Figure 12 according to the optimization result. From the optimization model in Figure 12, three significant changes in the SI housing construction delivery process compared to the cast-in-site housing construction delivery process can be seen. The changes are analyzed as follows:

- The housing design work of cast-in-site housing construction is divided according to specialties, such as building design, structural design, water and electricity supply design, and equipment design. However, that of the SI housing construction delivery process is divided according to different parts, including design of the S part, design of the I part, and design of the connections between the S part and I part. Designers with different specialties participate in each part of the design, which increases the communication and cooperation between designers. Meanwhile, the traditional serial design mode of building design → structural design → water and electricity supply design → equipment design is changed into the concurrent design mode in SI housing, in which the S part and I part can be designed simultaneously by the collaboration of designers with different specialties, significantly promoting design efficiency. In addition, the S part, I part and connections between them could be produced independently without disturbing each other, which reduces the waiting time between different works and improves production efficiency and supply efficiency.
- In the traditional serial construction mode, works in different specialties are implemented in a rigorous precedence order of main structure construction → secondary structure construction → refined decoration construction, with water and electricity supply construction and equipment construction inserted within this chain. Contractors with different specialties seldom collaborate together. Contractors in pre-works generally ignore their influence on follow-up works. When the follow-up workers encounter problems inhibiting their works arising from the pre-works, they have to do some repair or even rework on the pre-works, which is hugely wasteful because the pre-workers have possibly already left the construction site when their work finished and could not communicate with the follow-up workers in the parallel construction mode. In the SI housing construction delivery process, different parts of the housing are constructed and assembled in a parallel mode. Constructors for the S part, I part and connections between them create an integrated construction and assembly by planning together in a way that adequately considers the works in every part before starting. During the construction and assembly process, workers for different parts communicate with each other and solve the problems together whenever necessary. The parallel mode could reduce waste caused by conflicts and rework, and improve constructive efficiency.

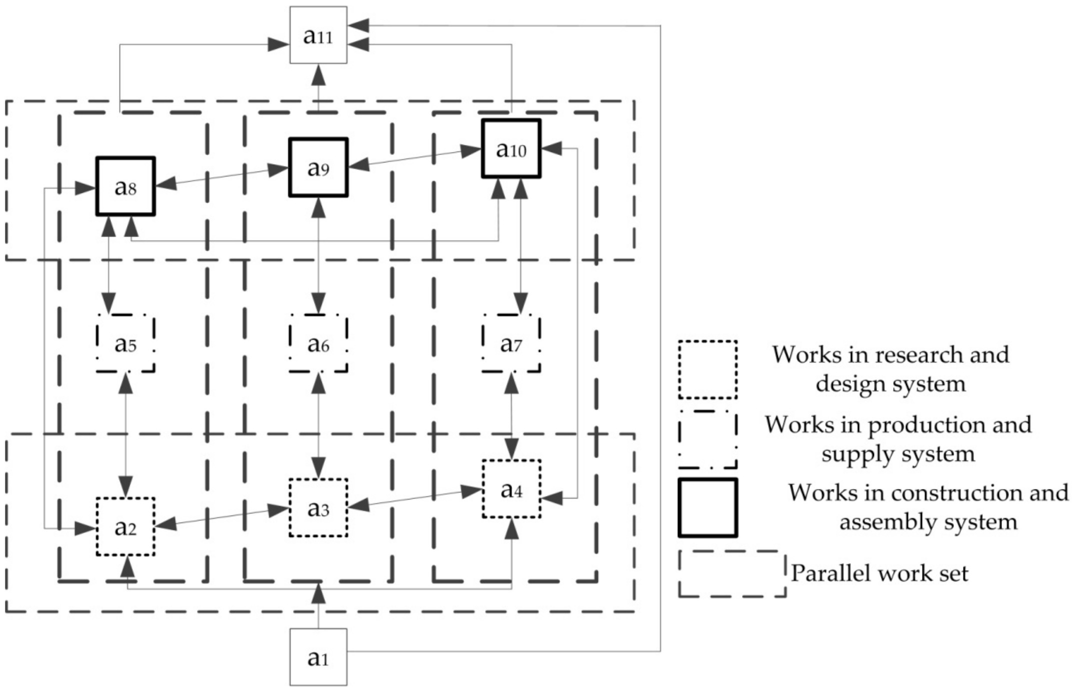

Figure 12. Model of the optimized SI housing construction delivery process.

In the traditional housing construction delivery process, when constructors encounter unreasonable or inconvenient works caused by design problems, they feed back the information to the designers in the corresponding specialty. However, design work that is divided into different specialties increases difficulties for communication. When the unreasonable or inconvenient works are in the cross-specialty, it is especially possible for different designers to pass the buck, which could increase communication costs and cause delays in the construction schedule. In SI housing, design work, production work and construction work are divided into the S part, I part, and connections between them, and workers with different specialties participate in each part, which increases the communication and cooperation between designers, producers and contractors. Therefore, problems caused by design in the production and supply process or in the construction and assembly process could be fed back to designers in a timely manner to acquire accurate corrections and adjustments, which not only ensures the smoothness of the current project, but also provides reference and guidance for the design of new SI housing projects.

6. Conclusions

SI housing has brought about a great deal of cooperative works among different stakeholders during the whole construction delivery process. Therefore, the traditional serial cooperation mode cannot be directly transferred to the SI housing construction. It is necessary to establish a new collaborative process to optimize the coupling works and iterations among the stakeholders in order to take full advantage of the SI housing system compared to the traditional housing construction.

A comprehensive DSM was established to measure the strength of the logical relationships among the main cooperation works, which provides a basis for the optimization of the SI housing construction delivery process. Furthermore, graph theory was applied to identify coupling work sets and eliminate repetition and iterations, so as to provide an optimized parallel construction delivery process for SI housing.

According to the results obtained from the optimized SI housing construction delivery process, the optimized parallel construction delivery process plays a significant role in promoting design efficiency. The design work of SI housing is divided into three functional parts: the S part, I part and connections between them. The S part and I part can be designed simultaneously by the collaboration of designers with different specialties, which increases the communication and cooperation between stakeholders. In addition, the S part, I part and connections between them could be produced independently without disturbing each other, which reduces the waiting time between different works and improves production efficiency and supply efficiency. Moreover, the parallel cooperation mode provides immediate feedback of design defects from the product process or assembly process to designers in order to acquire accurate correction and adjustment, which could promote efficiency in the whole construction delivery process, reduce time, and save construction costs.

There are some limitations in this paper: (1) SI housing construction delivery process was divided into three major sub-systems and only eleven main cooperative work items affiliated to the three major sub-systems, which could not cover all the cooperative works and their complex inner logic relationships in different delivery levels among all the stakeholders. (2) Graph theory which is generally applied to small or medium-sized project was employed for the DSM, therefore the significant characteristic of SI housing- adaptability analysis was not fully demonstrated in this research. As a consequence, the parallel cooperation model in this study only provides a reference for stakeholders in the macroscopic aspects. Therefore, additional research must be conducted to identify the cooperative works at a more specific level, and provide a more effective cooperative construction sequence. Future research will continue to focus on:

(1) Constructing a comprehensive DSM that covers the components and their complex inner logic relationships in different layers considering for system design, service life, adaptability and stakeholders in line with the characteristics of SI housing.
(2) Upgrading the DSM optimization based on intelligent methods to provide greater clarity of components organization and to optimize the parallel works and cross works in a more efficient way.
(3) Exploring the underlying cause as well as the transmission mechanism of iterations to predict rework risk and minimize building delivery duration and construction cost.

Author Contributions: Data curation, Y.Y.; Formal analysis, X.C.; Investigation, Y.Y. and X.Y.; Methodology, X.C.; Project administration, X.L.; Resources, X.C.; Software, X.C.; Supervision, X.L.; Writing–original draft, X.C.; Writing–review & editing, X.L.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 51868016.

Acknowledgments: The authors also would like to thank Miss Xiaoshu Lu in Southeast University for her assistance in date collection and Miss Mingfang Yang in Dalian University of Technology for her assistance in figure processing.

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

References

1. Nikolic, J. Building "with the systems" vs. building "in the system" of IMS open technology of prefabricated construction: Challenges for new "infill" industry for massive housing retrofitting. *Energies* **2018**, *11*, 1128. [CrossRef]
2. Jovanovic, J.; Grbic, J.; Petrovic, D. Prefabricated Construction in Former Yugoslavia. Visual and Aesthetic Features and Technology of Prefabrication. In Proceedings of the Post War Modern Architecture in Europe, Berlin, Germany, 22–24 July 2011.
3. Schmidt, R., III; Eguchi, T.; Austin, S. Lessons from Japan: A look at century housing system. In Proceedings of the 12th International Dependency and Structure Modelling Conference, DSM'10, Cambridge, UK, 22–23 July 2010; pp. 361–373.
4. Cao, X.; Li, Z.; Liu, S. Study on factors that inhibit the promotion of SI housing system in China. *Energy Build.* **2014**, *88*, 384–394. [CrossRef]
5. Paduart, A.; Debacker, W.; Henrotay, C.; Temmerman, N.D.; Wilde, W.P.; Hendtrickx, H. Transforming cities: Introducing adaptability in existing residential buildings through reuse and disassembly strategies for retrofitting. *Lifecycle Des. Build. Syst. Mater.* **2009**, 18–23.

6. Nikolic, J. New challenging approach for analysis and upgrading of massive building structure: Case study of New Belgrade post-war mega blocks. In *CESB 2013 Prague—Central Europe towards Sustainable Building 2013: Sustainable Building and Refurbishment for Next Generations; Grada for Faculty of Civil Engineering*; Czech Technical University in Prague: Prague, Czech Republic, 2013; pp. 1–10.
7. Slaughter, E.S. Design strategies to increase building flexibility. *Build. Res. Inf.* **2001**, *29*, 208. [CrossRef]
8. Rahim, A.A.; Hamid, Z.A.; Zen, I.H.; Ismail, Z.; Kamar, K.A.M. Adaptable housing of precast panel system in Malaysia. *Procedia-Soc. Behav. Sci.* **2012**, *50*, 369–382. [CrossRef]
9. Li, Y.; Xue, D.; Gu, P. Design for product adaptability. *Concurr. Eng.* **2008**, *16*, 220. [CrossRef]
10. Nikolic, J. Industrialized housing transformation capacity: Case study of post-war massive housing in Beograd. In *CESB2016 Prague—Central Europe Towards Sustainable Building 2016: Innovation for Sustainable Future*; Czeech Technical University in Prague: Prague, Czech Republic, 2016; pp. 229–236.
11. Hao, F.; Fan, Y.; Qin, P.; Cheng, L. Green building concept of SI housing system in Japan. *Housing Ind.* 2008. Available online: http://kns.cnki.net/kns/detail/detail.aspx?FileName=ZZCY2008Z1036&DbName=CJFQ2008 (accessed on 20 March 2008).
12. Fan, Y.; Cheng, Y. Past and present of sustainable open-house. *Architect* **2008**, *6*, 90–94.
13. Fukao, S. The history of developments toward open building in Japan. *New Archit.* **2011**, *6*, 14–17. [CrossRef]
14. Cao, X.; Li, X.; Zhu, Y.; Zhang, Z. A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *J. Clean. Prod.* **2015**, *109*, 131–143. [CrossRef]
15. Ministry of Housing and Urban-Rural Development of China (MOHURD). *The Technical Guideline for Construction of China-Skeleton-Infill Housing*; China Architecture & Building Press: Beijing, China, 2010; ISBN 1511217938.
16. Li, Z.; Han, X. Study on interface types and interface methods of the SI system. *J. Eng. Manag.* **2017**, *31*, 87–91. [CrossRef]
17. Shao, Y.; Zhao, S. Study on SI separation system of multi-story residential buildings in cities in northeast China. *J. Hum. Settl. West China* **2018**, 6–13. [CrossRef]
18. Chen, Y.; Ma, L.; Yang, Y. Built-in industrialization evaluation of SI-system housing based on improved F-AHP. *Constr. Econ.* **2018**, 102–107. [CrossRef]
19. Qin, S.; Jiang, H.; Wang, S. Public housing practice based on SI housing sustainable building theory in Japan. *Constr. Technol.* **2014**, *20*, 62–66. [CrossRef]
20. Xie, X.; Liu, H. Customized design strategy for SI residence with internet thinking—Thoughts inspired from the development of a century residential demonstration project. *Hous. Sci.* **2018**, *6*, 33–37. [CrossRef]
21. Yuan, M.; Li, Z.; Li, L. SI system housing virtual enterprise partners selection based on vector angle cosine. *J. Civ. Eng. Manag.* **2018**, *35*, 117–122. [CrossRef]
22. Browning, T.R. Applying the design structure matrix to system decomposition and integration problems: A review and new directions. *IEEE Trans. Eng. Manag.* **2001**, *48*, 292–306. [CrossRef]
23. Unger, D.; Eppinger, S. Improving product development process design: A method for managing information flows, risks, and iterations. *J. Eng. Des.* **2011**, *22*, 689–699. [CrossRef]
24. Danilovic, M.; Sandkull, B. The use of dependence structure matrix and domain mapping matrix in managing uncertainty in multiple project situations. *Int. J. Project Manag.* **2005**, *23*, 193–203. [CrossRef]
25. Danilovic, M.; Browning, T.R. Managing complex product development projects with design structure matrices and domain mapping matrices. *Int. J. Project Manag.* **2007**, *25*, 300–314. [CrossRef]
26. Schmidt, R.I.; Deamer, J.; Austin, S. *Understanding Adaptability Through Layer Dependencies*; Design Society: Leicestershire, UK, 2011; pp. 1–12.
27. Schmidt, R., III; Eguchi, T.; Austin, S.; Gibb, A. What Is the Meaning of Adaptability in the Building Industry? In *Open and Sustainable Building*; Labein-TECNALIA: Derio, Spain, 2010; pp. 233–242.
28. Robert, S., III; Jason, D.; Simon, A. Understanding adaptability through layer dependencies. In Proceedings of the International Conference on Engineering Design, ICED11, Lyngby, Denmark, 15–18 August 2011., 15–18 August 2011.
29. Robert, S., III; Kasper, S.V.; Simon, A. Evaluating the adaptability of an industrialized building using dependency structure matrices. *Constr. Manag. Econ.* **2014**, *32*, 160–182. [CrossRef]
30. Smith, R.P.; Eppinger, S.D. A predictive model of sequential iteration in engineering design. *Manag. Sci.* **1997**, *43*, 1104–1120. [CrossRef]

31. Smith, R.P.; Eppinger, S.D. Identifying controlling features of engineering design iteration. *Manag. Sci.* **1997**, *43*, 276–293. [CrossRef]
32. Smith, R.P.; Eppinger, S.D. Deciding between sequential and concurrent tasks in engineering design. *Concurr. Eng. Res. Appl.* **1998**, *6*, 15–25. [CrossRef]
33. Zhang, X.; Skitmore, M.; Peng, Y. Exploring the challenges to industrialized residential building in China. *Habitat Int.* **2014**, *41*, 176–184. [CrossRef]
34. Sharman, D.M.; Yassine, A.A. Characterizing complex product architectures. *Syst. Eng.* **2004**, *7*, 35–60. [CrossRef]
35. Tang, D.; Qian, X.; Liu, J. *Product Design and Development Based on Design Structure Matrix*; Science Press: Beijing, China, 2009; ISBN 9787030228291.
36. Liu, L.; Hu, D.; Li, B. Survey of optimal algorithm of design process model based on DSM. *Comput. Eng. Appl.* **2009**, *45*, 22–25. [CrossRef]
37. Gebala, D.A.; Eppinger, S.D. Methods for analyzing design procedures. In Proceedings of the International Conference on Design Theory & Methodology, Scottsdale, Arizona, 13–16 September 1991.
38. Wang, Y.; Xing, Y.; Ruan, X. Information modeling and re-engineering for Design Process. *Comput. Integr. Manuf. Syst.* **2002**, *8*, 111–114. [CrossRef]
39. Yassine, A. Engineering design management: An information structure approach[C]// Innovation in Technology Management-the Key to Global Leadership Picmet 97. In Proceedings of the Portland International Conference on Management & Technology, Portland, OR, USA, 31–31 July 1999. [CrossRef]
40. Whitfield, R.I.; Duffy, A.H.B.; Gartzia-Etxabe, L.K. Identifying and evaluating parallel design activities using the design structure matrix. In Proceedings of the 15th International Conference on Engineering Design (ICED'05), Melbourne, Australia, 15–18 August 2005.
41. Yao, Y. Product development process intelligent analysis and improvement technology in PDM. *China Mech. Eng.* **2004**, *15*, 1857–1861. [CrossRef]
42. Abdelsalam, H.M.E.; Bao, H.P. A simulation-based optimization framework for product development cycle time reduction. *Eng. Manag. IEEE Trans.* **2006**, *53*, 69–85. [CrossRef]
43. Mcculley, C.; Bloebaum, C.L. A genetic tool for optimal design sequencing in complex engineering systems. *Struct. Multidiscip. Optim.* **1996**, *12*, 186–201. [CrossRef]
44. Kenneth, H.R. *Discrete Mathematics and Its Applications*; China Machine Press: Beijing, China, 2015; ISBN 9787111453826.