Two Technological Paths towards Construction Industrialization: Prefabricated and On-site Industrialized Construction

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***Abstract*—Industrialized construction (IC) is a method with better productivity, quality, safety, and sustainability, which has attracted widespread attention from the global construction industry. Previous studies have mostly focused on prefabricated construction (PC), neglecting discussions on on-site industrialized construction (OIC). In concrete buildings, the theoretical comparison between the two needs to be evolved and incorporated with a global view and understanding. Therefore, this study constructed a theoretical comparative framework between PC and OIC, systematically sorting out their concepts, characteristics, goals, construction logic, and ecological relationships. Finally, based on this framework, this study proposes recommendations for selecting IC technology paths from aspects such as building height, structural construction, component properties, and enterprise level. The framework between PC and OIC emphasized in this paper has the potential to supplement the theoretical system of IC and provide guidance for the diversified development of global construction industrialization.**

***Keywords*—concrete buildings, prefabricated construction, on-site industrialized construction, theoretical comparative framework, technological paths**

I. Introduction

The global construction industry is facing many challenges such as skilled labor shortage, high safety risks, low production efficiency, high resource consumption, and severe environmental pollution [1]. The urgency these challenges present to policymakers has led to numerous regulatory obligations to reform the construction industry toward sustainable development. Many countries and regions advocate drawing on the industrialization experience of the manufacturing industry to promote the transformation of the construction industry towards industrialization [2, 3]. The theoretical advantages of IC as a feasible construction method in improving key goals such as efficiency, cost, quality, and environment have been verified by many scholars [4–6]. However, in practice, due to the diversity of building functions, uniqueness of building products, diversity of product types, complexity of construction processes, and temporary nature of engineering projects [7], it is difficult for the construction industry to fully replicate the industrialized production organization model of manufacturing [8]. In addition, due to the different types of building structures, their production characteristics vary greatly. Therefore, the industrial transformation of the construction industry should be based on meeting the characteristics of factory production, standardization, mechanization, modularization, and integration, developing IC and technologies suitable for different conditions according to local conditions. Steel and wooden structures are naturally suitable for factory prefabrication and on-site assembly, and PC is the best choice for industrial production of both. For concrete structure buildings, relying solely on PC to achieve construction industrialization is one-sided, and the degree of prefabrication cannot represent the level of industrialization [8, 9].

As shown in Fig. 1, according to different parts of construction, the IC methods of concrete buildings include industrialization of the main structure and industrialization of the interior decoration. The latter includes the industrialization of mechanical and electrical installation and the industrialization of decoration. They are aimed at the interior of buildings, emphasizing that equipment, pipelines, and components are completely manufactured by factories and delivered to the site for direct assembly on the main structure. Therefore, for them, the PC is an irrefutable path for industrial implementation. The industrialization technology path of the main structure includes PC and OIC. PC emphasizes that building components are pre-produced in the factory and then transported to the construction site for assembly [10]. OIC emphasizes the use of advanced technologies and equipment such as systematic formwork, climbing frames, and scientific management methods for factory-like construction on site, where the pouring and connection of concrete are integrated [11].

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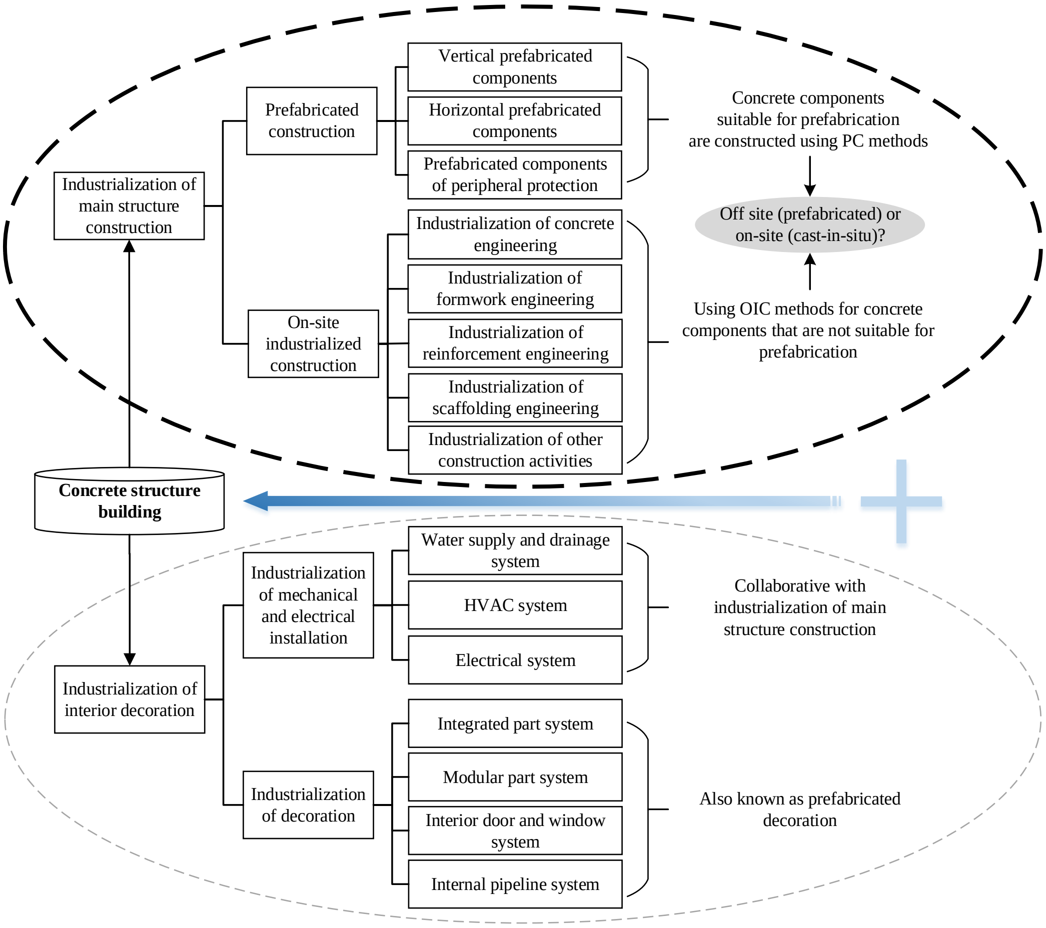

Fig. 1. IC methods for concrete structure building.

In concrete buildings, the construction of the main structure accounts for about 70% of the workload and is the most fundamental and critical sub-project. However, the technological path of industrialization of the main structure largely relies on PC and ignores OIC. Therefore, the debate between “off-site (prefabrication) or on-site (cast-in-situ)” has sparked some scholars [12]. It can be seen that the industrialization of the main structure is crucial and also the main contradiction point of IC. However, there seems to be limited systematic research on PC and OIC. Therefore, this study focuses on the discussion of PC and OIC in concrete buildings, sorting out and comparing their concepts, characteristics, goals, construction logic, and relationships, providing suggestions for the selection of IC paths, to promote the diversified development of construction industrialization.

II. Review of IC in Different Countries

In recent years, IC has aroused widespread concern in the construction industry, which has been extensively studied in developed and developing countries worldwide. The research and development status varies due to differences in problem scenarios, industry backgrounds, product types, and technologies [13]. As an “integrated term”, the expression of IC differs from countries and regions, which reflects the development characteristics of IC to a certain extent, as shown in Table I.

TABLE I. Terms of Industrialized Construction in Different Countries

Country	IC terms	Sources
UK	Modern Methods of Construction (MMC)	[2]
the United States	Prefabrication, Preassembly, Modularization, and Off-Site Fabrication (PPMOF)	[16]
Canada	Modular Construction / Building	[17]
Sweden, Norway, Denmark	Timber-Framed Multistory Buildings	[18]
France, Australia	Off-Site Manufacturing Housing / Off-Site Precast Concrete Buildings	[19]
Japan	Prefabricated House Building, Housing Industrialization, Mass Customization	[20]
Singapore	Prefabricated Prefinished Volumetric Construction (PPVC)	[21]
Hong Kong	Prefabricated Housing Production(PHP), Prefabricated Residential Building (PRB), and Modular Integrated Construction (MiC)	[22]
China	Prefabricated Buildings / Construction, New Construction Industrialization, On-site Industrialized Construction	[6]

The expression of IC can be roughly divided into four perspectives in terms of affixes [14]: 1) Emphasizing the spatial change of the production site of architectural elements, such as "Off-site", implying a large number of construction activities are transferred from on-site to off-site, including fixed factories and nomadic factories. 2) Highlighting the time alteration of different construction activities in the whole process, such as "Pre-assembly and Pre-work", adjusting the logical order of construction activities by changing work forms, or adopting concurrent and overlapping working methods to reduce the waiting time of traditional construction ways. 3) Underlying the advanced characteristics of theory, technology, and management of construction, such as "Modern methods of construction", and paying attention to the advancement of standardization, mechanization, and IT application; 4) Stressing the particularity of systems and products compared with traditional buildings, such as "Housing Industrialization", focusing on the additional attributes and promotional value brought by industrialization characteristic of building products.

From the perspective of structural types, multi-story houses and single-family houses featuring wooden structures account for a considerable proportion of residential types in countries including the United States, Canada, Sweden, Norway, Denmark, etc. It can be argued that wooden framed buildings are naturally suitable for prefabricated or off-site construction methods of IC. However, high-rise residential buildings featuring reinforced concrete structures are widely built in Japan, Singapore, China, and Hong Kong. For such types of residential buildings, the pursuit of the maximum rate of prefabrication may not be the best way to realize IC, the standardization of project implementation and enterprise business processes can also play an important role [8]. The research and application of composite prefabricated building systems in Japan is one of the examples of efforts seeking the optimal combination between "prefabricated and cast-in-situ", and also between "main structure and interior decoration" [15]. Singapore and Hong Kong are pushing ahead with prefabrication and modular technology in government-led projects. In China, PC is vigorously promoted and some pioneering construction enterprises have also developed a series of OIC systems with the guiding ideology of industrialization, such as SSGF, 5+2+X, aerial building machines, etc [11].

III. Comparative Analysis of PC and OIC

In this section, a comparative theoretical analysis of PC and OIC is conducted from the aspects of concepts, characteristics, goals, construction logic, and relations (as shown in Fig. 2).

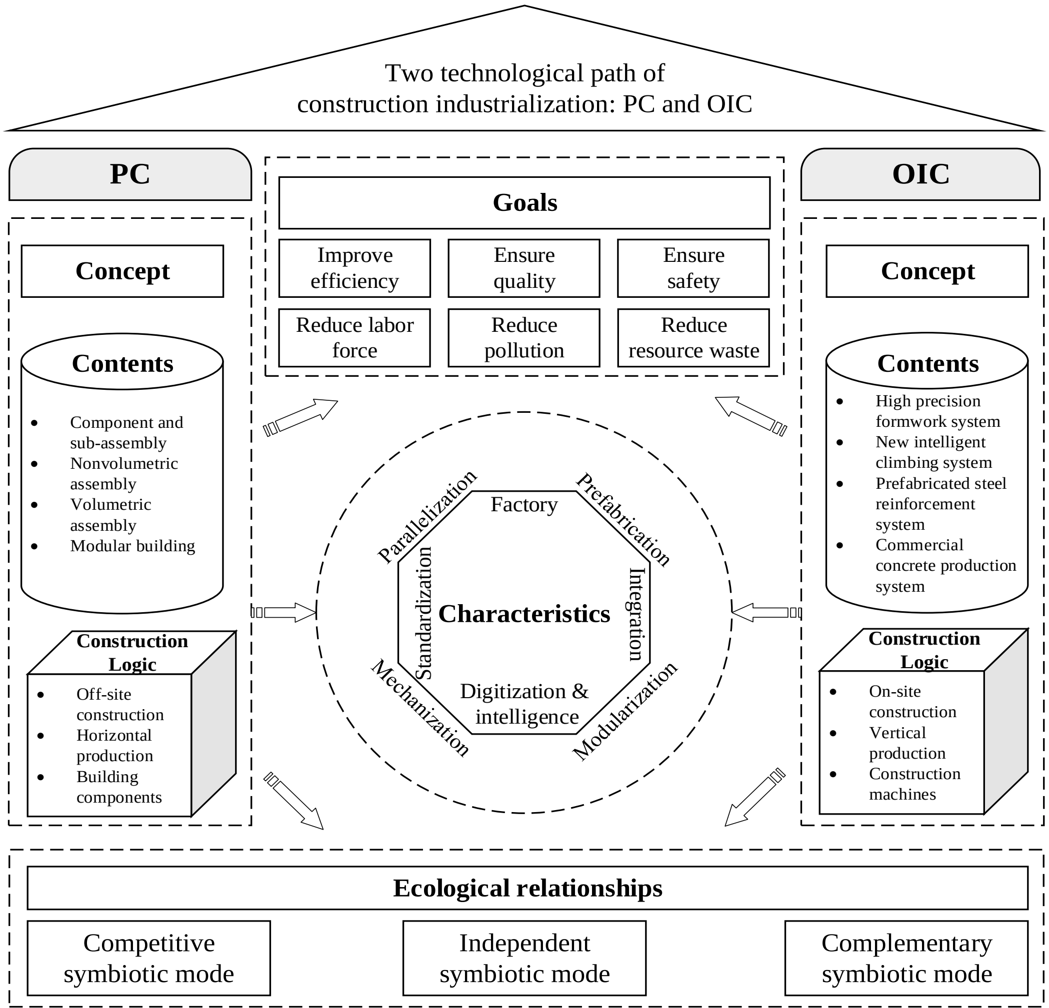

Fig. 2. The framework of comparative theoretical analysis of PC and OIC.

A. The Concept of PC and OIC

PC refers to the construction method in which certain amounts of building components, modules and elements are produced and pre-assembled off-site in standard and modular ways, and then transported to the construction site for assembly. According to the most widely acknowledged PC grading standard hitherto proposed by Gibb, PC could be divided into four levels based on the degree of off-site prefabrication [8]: component and sub-assembly (e.g. lintels), nonvolumetric assembly (e.g. 2-dimensional precast concrete wall panels), volumetric assembly (e.g. volumetric bathrooms), and modular building (e.g. 3-dimensional modules which form the fabric of the building structure).

OIC is a construction method where building products are directly built on-site with the guidance of industrialization. The construction site is regarded as a temporary factory while general construction machinery or tools, advanced information technology, and standard production management are adopted in the entire construction process [11], and is also argued as an improvement of the traditional cast-in-situ method. In practice, various systems are involved including on-site lightweight and high-precision formwork systems (aluminum formwork, etc.), new intelligent climbing systems, integrated prefabricated steel bar systems (formed steel cage, etc.), commercial concrete production, supply, and pouring systems, etc.

B. Characteristics of PC and OIC

The key characteristics of IC include temporary factory, prefabrication, standardization, modularization, integration, mechanization, digitization and intelligence, and parallelization [11]. PC has traditionally been considered as the best way for IC with the above features whereas OIC performs similarly in practice.

1) Temporary Factory. Obviously, the production of prefabricated components needs to be finished in the factory. OIC also draws on the logic of the manufacturing industry and designed an on-site virtual factory using intelligent climbing frames, aluminum formwork, and awnings, which also creates a factory-like environment.

2) Prefabrication. PC lays stress on the prefabrication of the product itself as construction components are prefabricated. The prefabrication in OIC is reflected in construction tools (such as aluminum formwork) and building materials (such as prefabricated high-performance concrete and prefabricated steel reinforcement cages).

3) Standardization and modularization. Standardization and modularization in PC are reflected in building products such as prefabricated components (physical attributes), while OIC puts more emphasis on the standardization of the process and the modularization of the activities of the final construction product (process attributes). In addition, OIC also pays attention to the standardization and modularization of general construction machinery and tools.

4) Integration. The integration of IC is manifested in three aspects, firstly including the combination of architecture, structure, electromechanical system, and decoration; secondly is the integration of design, process, and assembly; Then comes technology, market, and management. Compared with PC, OIC carries the integration characteristic more distinct and could be easier to put into practice.

5) Mechanization. Replacing manual labor with mechanical production is one of the basic characteristics of industrialization. A large number of mechanical equipment is applied in PC both in the factory and on-site lifting processes. In OIC, on-site mechanization has greatly augmented and the production of materials such as concrete and steel bars has also been mechanized.

6) Digitization and intelligence. Unlike mechanization, digitization and intelligence aid in reducing mental labor rather than manual labor. To improve the quality and productivity of IC in the new era, digital technology and intelligent equipment are extensively employed which can also be seen in PC and OIC development.

7) Parallelization. The idea of interspersed construction and concurrent engineering is well reflected in PC and OIC to reduce the duration by trading space for time.

C. The goals of PC and OIC

The application of innovative technology should be centered around particular problems and goals. In the face of the predicament of the construction industry resulting from the shortage of skilled labor, high safety risks, low production efficiency, high resource consumption, serious environmental pollution, etc., IC is vigorously promoted as an effective solution globally to achieve goals including efficiency improvement, labor reduction, quality and safety guarantee, and environmentally-friendly construction. Therefore, innovative technology in various forms that meets the characteristics and objectives of industrialization should all be considered as IC technology.

As an innovative technology, the PC has been proven to achieve these goals in IC [14]. However, some deficiencies have also been exposed in practice like concerns about construction quality and the lack of vigor in efficiency improvement, and a critical review of technology and organization management now available, is warranted. Compared to the traditional cast-in-situ construction method, OIC makes improvements in four aspects of engineering including steel reinforcement, formwork, concrete, and scaffolding when reserving the original organization process. It has made achievements in the goals mentioned above and could be much easier for enterprises to accept and apply. Many technologies in OIC are adopted like the processing and distribution of formed steel reinforcement bars, the high-precision prefabrication of shaped formwork, the combination of concrete commercialization and pump, the application of intelligent climbing, etc., ensuring construction quality, efficiency, and reduce the dependence on manual labor. In a factory-like environment with high technology, workplace safety is raised when environmental pollution declines. In addition, some large-scale integrated and mechanized construction platforms applied on-site also belong to the scope of OIC, which can reduce the amount of on-site labor and environmental impact.

D. The Construction Logic of PC and OIC

In terms of construction logic, PC is the opposite of OIC.

1) The production locations are respectively off-site and on-site. PC emphasizes off-site factory production, which is an integrated mode of factory production and on-site assembly. OIC focuses on on-site factory construction and is a terminal product integration of information, logistics, technology, and management for on-site construction, replacing manual labor with innovative technology and advanced machinery.

2) The production processes are horizontal and vertical respectively. Prefabricated components with horizontal production lines in off-site factories, in which components are moved and mold fixed. In OIC, the concrete is continuously cast into a standard floor structure according to the shape of one floor assembled by the prefabricated formwork, where components are fixed but mold moved.

3) The object of industrial improvement are respectively building components or parts and construction machinery or tools. PC achieves industrialization through the prefabrication and assembly of building components while OIC deploys on-site work with advanced, general construction machinery and tools to improve traditional cast-in-situ construction methods.

E. The Relationship between PC and OIC

Empirical research in numerous industries suggests that long-term interactions between different innovative technologies may influence their development in various ways. Radical innovations may succeed in replacing, transforming, or even reconfiguring existing socio-technical systems, or they may fail to gain sufficient momentum to unlock the potential for groundbreaking change and improvement. The symbiotic relationship between technologies can be divided into competition, independence, and complementation (as shown in Table II) [23]. In the meanwhile, the co-evolution between technologies is also influenced by external ecology, such as policy, economy, society, natural environment, etc.

TABLE II. THE ECOLOGICAL RELATIONSHIP BETWEEN TECHNOLOGIES

Relationship Types	**Relationship Effects**		**Relationship Characteristics**
	A	B	
Competition	−/+	+/−	Provide similar services, compete for dominance, and inhibit each other.
Independence	0	0	There is no direct influence on each other.
Complementation	+	+	Complement each other and collaborate in many functions.

In the industrial construction technology ecology, these three interaction modes exist similarly in PC and OIC, and technology development paths can be transformed into each other under the influence of the external environment.

1) Competition: In the main structure of concrete buildings of the IC, there is a competitive relationship between PC and OIC. Concrete components can be precasted or casted in situ, and the adoption of any method will directly affect the other. PC and OIC share the same goal of industrializing the traditional decentralized construction process, and it poses a direct threat to the development of OIC when the development path dependence of PC now exists.

2) Independence: The independence relationship is mainly present in the industrial construction of the main structure and the internal structure in PC and OIC. As there is no evident overlap between the target markets and the resources required, the application of PC in interior decoration is dependent on the adoption of OIC in the main structure. It can be regarded that the interaction between OIC in the main structure and PC in interior decoration is not significant.

3) Complementation: Unlike competition, PC and OIC can give full play to their respective advantages in the construction of the main structure, and work together to promote industrialization. For example, horizontal components (such as floors, stairs, air conditioning panels, balconies, etc.) can adopt PC technology, while vertical components (columns, load-bearing walls, etc.) apply OIC technology. In this way, both the quality and the efficiency can be guaranteed as PC and OIC complement each other.

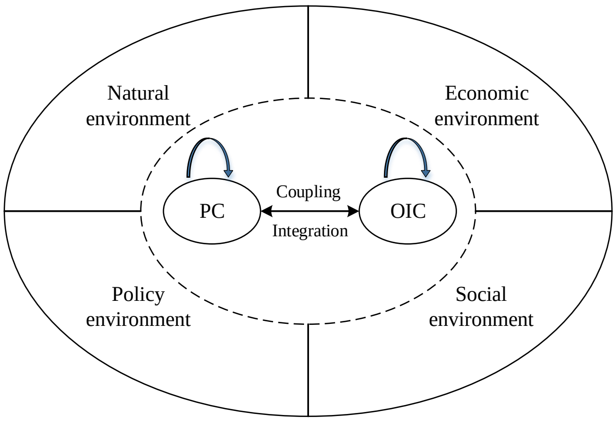

Fig. 3. Technology ecology of PC and OIC.

The technology ecology between PC and OIC will continuously adjust and adapt according to the natural, economic, policy, and social environment, developing gradually into a symbiotic model with weak competition and strong complementation in IC (as shown in Fig. 3).

IV. SELECTION OF INDUSTRIALIZED CONSTRUCTION TECHNOLOGY PATHWAYS

There is no absolute superiority or inferiority between PC and OIC and therefore reasonable integration should be carried out according to different scenarios.

1) In consideration of the height of the building, medium and low-rise buildings can give priority to PC technology and explore raising the prefabricated rate; High-rise buildings can preferentially adopt OIC technology when taking PC as a supplement to adapt to the structural performance for comprehensive benefits.

2) From the structure of the building, the industrialization of interior decoration has reached a high level of maturity. Interior decoration is naturally suitable

for PC construction with small component volume and high added value. The components of the building shell are relatively large and bulky with low added value, and there are still concerns about its safety and quality on the market. Taking all these factors into consideration, OIC technology should be adopted first thereafter promoting PC technology gradually with steady steps.

3) From the perspective of component attributes of buildings, PC and OIC technology can be preferentially applied for horizontal non-load-bearing components and vertical load-bearing components respectively.

4) In light of the enterprises, PC research and development can be vigorously advanced in enterprises with high-tech and management skills for IC. For most ordinary enterprises, priority can be given to OIC technology for being easier to master while simultaneously promoting PC technology in an orderly way to IC.

V. Conclusions

IC is a crucial way towards pushing ahead construction industry transformation globally, in which technological path varies with different structural types of buildings. This study analyzed PC and OIC of concrete structure building from diverse perspectives and a theoretical framework for comparative analysis of PC and OIC was established. In this framework, the concept of PC and OIC was summarized first, then came differences analysis in the characteristics of temporary factory, prefabrication, standardization, modularization, integration, mechanization, digitization and intelligence, and interspersed construction while discussing the goals of both. Subsequently, the construction logic of PC and OIC was compared from three aspects including construction site (off-site and on-site), production process (horizontal and vertical production), and object of industrial improvement (building components and construction machinery). Finally, in-depth discussions were conducted on three kinds of relationships (competition, independence, and complementation) between PC and OIC for symbiosis. Based on this framework, this study put forward suggestions on the choice of IC technological path from different scenarios. The research findings complement the knowledge system in the field of IC and provide a reference for construction industrialization development in a diversified way. In the follow-up research, the relationship between PC and OIC can be expanded under the guidance of the technology symbiosis theory to explore the integration and innovation mechanism of PC and OIC.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Shengbin Ma conducted the global study and completed the paper in English; Zhongfu Li revised important knowledge content critically; Shuran Zhang gave some good suggestions and made a comprehensive English revision. All authors had approved the final version.

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