Impact Analysis of Complexity Drivers in the Supply Chain of Prefabricated Houses

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Abstract

The lack of living space has recently increased particularly in urban centers. This deficiency cannot be remedied with the productivity status quo in the construction industry. One opportunity to significantly increase the productivity of the construction industry is the industrial modular construction. In order to achieve increased productivity, the value chain must act across the entire organization. A supply chain management is required to exploit the potential of the prefabricated construction. In order to develop a specific supply chain management, the corresponding complexity factors along the value chain must be known. The aim of the study is to quantify the essential factors which influence the value chain for prefabricated houses and form a basis for the future development of a supply chain management. The results of this scientific work clearly show that although an industrial modular production is carried out, the highest complexity drivers are still found on the construction site as well as in the logistics from the module production to the construction site. In addition, it is also apparent that special requirements as well as the size of the modules are decisive factors and as such need to be considered during the future development of the supply chain management concept.

Keywords: supply chain management, prefabrication, modular housing, complexity, measurement

1. Introduction

The urbanization drastically increased the number of people living in cities. According to a study of the United Nations 50 % of the world population is currently living in cities. This number is expected to increase up to 70 % by 2050 (United Nations Human Settlements Programme, 2008). At the same time the productivity in the construction sector hardly increased in the last decades (Vrijhoef & Koskela, 2000). In Germany for example, the productivity showed no significant growth in the last years, which has a direct impact on the housing market. According to the European commission the situation of the housing market is in some regions critical with no improving trend (European Commission, 2016). Furthermore the construction industry was barely affected by technology innovations or the digitalization (World Economic Forum, 2016). Facing greater obstacles now and in order to create sufficient and affordable living space, the construction industry needs to change its way of thinking. One way of doing that is to use modularization methods (Mullens & Kelley, 2004; Grundke & Wildemann, 2015).

Modularization, also known as a platform concept, becomes a success factor in different industrial areas, in order to overcome challenges between the contradictory targets of standardization and individualization (Johnsson; Jansson & Jensen, 2013). The main idea of the prefabrication of housing modules is to produce the house modules in a highly standardized production line, similar to the automotive industry (Gann, 1996; Hines, 2012). The house is completely decomposed into standardized elements and produced in factories (Ericsson & Erixon, 1999; Huang et al., 2006). Contrary to traditional construction the main creation of value occurs in production and so the time required on the building site is reduced to a minimum. In extreme cases the percentage of prefabrication can increase up to 80 % (Furuse & Katano, 2006).

To obtain the benefits of the prefabrication concept a well-organized supply chain is of utmost importance. In a well working supply chain the coordination of all participants of the overall house project is an important aspect to delivering the house on time, with low costs and high quality standards (Lessing, 2006; Grundke & Wildemann, 2015). Therefore a supply chain management needs to accompany the whole construction process from the planning

to the delivery of the house (Bygballe; Jahre & Swärd, 2010). The high number of companies involved in the process as well as the transportation and the construction/assembly of the modules on-site are some of the complexity drivers for the supply chain management (Arantes; Ferreira & Costa, 2015; Cheng; Law; Bjornsson; Jones & Sriram, 2010). In order to develop a supply chain management concept for the modular construction sector, it is necessary to examine the relevant complexity drivers and evaluate their importance and correlation to the supply chain management. Thus, the aim of the paper is to define which complexity drivers are most important to be considered in the modular construction supply chain as well as to be the base concept for further research in this area.

The supply chain typology can be divided into four main strategies; make-to-stock, make-to-order, deliver-to-stock and deliver-to-order (Werner, op. 2013). The construction business is project work whereby the supply chain is associated to the make-to-order strategy (Vrijhoef & Koskela, 2000). This is also the case in the modular housing supply chain. Typically, the order process starts with the configuration of the houses by the customer. For that a product configurator can be used to visualize the house and fix the prices in real time (Kim, 2015). A difference of the manufacturing supply chain compared to the construction supply chain of prefabricated modules is the assembly site of the product. In the traditionally industry the whole product is produced and assembled on the construction site (Lundesjo, 2015). In case of the prefabrication housing supply chain a high degree of the house is finalized during production only. The last steps take place on the construction site. To optimize this complex supply chain, with the influence of the different subcontractors, architects, house owners, a specific supply chain management needs to be implemented. In analogy to the automotive industry, the customer is included in Tier 0, Tier 1 includes the module manufacturer and the architect, the subcontractors are included in Tier 2 and Tier 3 consists of the suppliers for materials and semi-finished products (Meng, 2012). In order to achieve a higher transparency, in this paper the complexity drivers of a supply chain can be classified into three different categories: upstream complexity, internal manufacturing complexity and downstream complexity (Bozarth; Warsing; Flynn & Flynn, 2009). Similar to the complexity drivers in the manufacturing process for goods, the housing supply chain contains the same division of complexity drivers.

Prior to the start of the production process there are complexity drivers for example in the planning process of the house. The category upstream complexity contains per definition drivers which are native to areas of the supply chain base. Potential factors of this category include aspects like the number of suppliers, the delivery time and reliability (Bozarth et al., 2009). In order to transfer the modular housing supply chain into this pattern, the customer as well the architects and engineers need to be included into this category (Grundke & Wildemann, 2015).

The category internal manufacturing complexity contains all aspects which have a direct or indirect influence on the manufacturing facility´s product, processes and control systems (Flynn & Flynn, 1999; Bozarth; Warsing; Flynn & Flynn, 2009). Examples for the housing supply chain are the number of parts used, the control system and the information technology. To achieve a high prefabrication degree, the modular manufacturers use a true automated moving production line. Similar to the automotive industry the product, in this case the house modules, shift through different stations where different crews perform specific tasks (Ganiron, JR & Almarwae, 2014). Considering this complexity drivers in the planning process of a building project the relations between each other also need to be managed. Therefore a well thought communication system, which includes all participants of the supply chain, needs to be developed (Briscoe & Dainty, 2005; Briscoe; Dainty & Millett, 2001). In the construction industry the building information modelling (BIM) is used (Azhar, 2011). This has the benefit of a better coordination within the supply chain, which ensures a higher efficiency during in the whole process. Besides that all stakeholders have a transparent access to all relevant data for the building project (Kreider & Messner, 2013).

In addition to the upstream and internal manufacturing complexity there are also critical complexity drivers in the downstream area of the construction supply chain. The factors of the downstream complexity originate from the sales market of the product (Bozarth et al., 2009). One driver which could be assigned to this category is the degree of individualization of the products, which again has a direct impact on the production (Olsson, 2000) (Figure 1.).

After having identified the deficiencies of the construction industry and its included supply chain, the modularization approach could result in a substantial benefit towards the conventional construction. In order to achieve this an integrated supply chain management is required. Through the before mentioned complexity areas, a supply chain for the prefabrication of housing modules can be identified and analyzed to develop the basis for a supply chain management concept. The aim of the current paper is to identify important complexity drivers, which have the potential to significantly influence the supply chain management in the prefabricated housing industry.

More specifically, this research paper will focus on the material flow in the supply chain, which is a complexity driver contained in all three categories of the supply chain. Regarding the current state of the art in this research

paper the primary hypothesis is that the area between the construction site and the module manufacturer (downstream) has the highest degree of complexity. To prove this hypothesis the main complexity drivers were analysed in one-on-one interviews and evaluated with an online-based questionnaire.
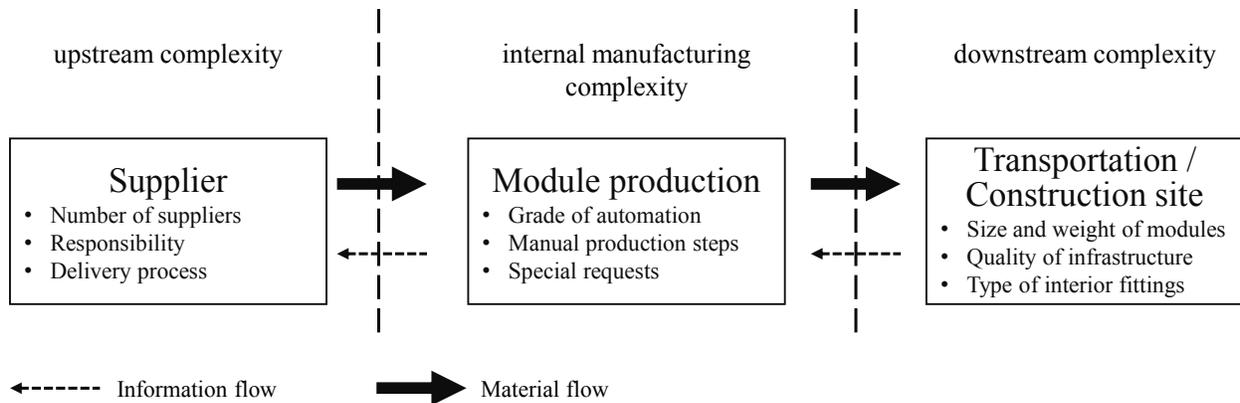

Figure 1. Complexity drivers in the construction supply chain are divided into three categories

2. Methodology and Research Design

2.1 Research Objectives

The success of a well-coordinated supply chain in the modular housing will deeply depend on an adequate management and controlling concept. To structure an extensive management firstly the complexity drivers in different stages must be defined in order to afterwards develop a supply chain management concept. The study provides a ranking of the main complexity drivers in the different stages of the value chain.

The research paper wants to provide answers to the following questions:

   I. What are the complexity drivers in the supply chain of the modular housing industry regarding the material flow?

  II. Which area in the supply chain shows the most difficult aspects to manage?

 III. What is the influence and impact on each driver on the other areas?

2.2 Variables

In order to answer these questions the main complexity drivers in each stage of the order process in the prefabrication of houses were derived from the literature and afterwards evaluated in expert interviews. After the evaluation of the drivers a questionnaire was constructed, which had the aim to quantify the importance of these factors regarding their impact on the supply chain. In order to accumulate the number of different complexity drivers, influencing variables of different stages in the supply chain are being looked at. For this the supply chain in the modular housing industry was divided into four steps regarding the material flow:

- between the supplier and the module manufacturer,
- within the module production,
- between the module manufacturer and the construction site and
- on the construction site.

Parties like the architects and the owner of the house were not considered as a supply chain stage in this research paper in order to reduce the complexity. Furthermore, these parties are indirectly represented by the variable "range of special request", which can drive the complexity of the supply chain process regarding additional wishes of customers or architects.

Between the supplier and the module manufacturer

To achieve a high degree of prefabrication and an optimized supply chain process the vendor parts must be supplied

in a just-in-time process in order for the complexity to be minimized. Semi-finished products such as kitchens and bathrooms should be delivered just-in-sequence to avoid more complexity within the actual supply chain. Another factor which has a direct influence on the supply chain is the number of suppliers. Similar to the negative relation between the unique used parts and the complexity of the supply chain (Fisher; Ramdas & Ulrich, 1999), the number of suppliers are a significant complexity driver. Therefore, the following parameters where used in the questionnaire:

- Number of suppliers
- Delivery times and reliability of suppliers
- Kind of delivery process (just-in-time, just-in-sequence)
- Supplier's willingness to take responsibility for additional processes.

Within the module production

To evaluate the complexity within this stage, aspects like the individualization of the product or the volumes of the manual production steps can increase complexity. To include all parameters in the complexity contemplation the following aspects were considered:

- Grade of automation in the manufacturing process
- Steadiness of production schedules
- Volume of manual production steps (plumbing and cabling)
- Range of special requests.

Between the module manufacturer and the construction site

A very crucial stage in the order process for a prefabricated house is the logistics from the module manufacturer to the construction site. In order to achieve the previously combined aspects like the delivery time and the costs, the weight and the size of the module have a significant impact and pose complexity drivers within the supply chain. Except for these drivers, the quality of infrastructure on the last transportation mile and the delivery time and reliability of the carriers are also drivers which have a direct impact on the management of complexity within the supply chain. The following parameters were considered in the analysis:

- Delivery times and reliability of carrier
- Size and weight of modules shipped
- Quality of infrastructure of the last transportation mile
- Kind of delivery process (just-in-time, just-in-sequence).

Construction site

To finalize the house, another crucial stage of the value chain involves complexity drivers. In the finishing process on the construction site the numbers of subcontractors as well as the degree of infrastructure preparation on site are also aspects which make the whole process more complex. Additionally, to that the delivery times and reliability of subcontractors as well as the difficulty of the module mounting process are further complexity drivers in this stage.

- Delivery times and reliability of subcontractors
- Degree of infrastructure preparations onsite
- Type and volume of interior fittings
- Difficulty for module mounting process.

3. Results

3.1 Data Collection

The data were collected through an online based questionnaire, which was available from September to October 2016. The online based questionnaire was available in two different languages; English and German. To guarantee the quality of the survey mandatory drag-and-drop questions were included into the questionnaire. Only participants who successfully answered these questions received the additional questions, which included the separate complexity drivers of each stage in the supply chain. Potential participants where directly contacted via email. The contact details of the participants were collected during other research and consulting projects in the field of modular housing. They include architects, designers, general contractors, project developers, suppliers and subcontractors. In order to enhance the quality of the research multiple observations were used. The data were analysed with the SPSS

Statistics 23 (IBM) software.

In total 122 people participated in the questionnaire, which, after the elimination of all faulty data sets, gave a number of 100 valid data sets ready to be used to calculate the results. In total 24 architects, 15 house owners and project developers, 18 contractors, 15 subcontractors, 13 researchers, 9 suppliers and 2 consultants participated in this questionnaire. 4 data sets did not include a specific job description of the participants. To receive an overview over the origin of the complexity drivers in each stage in the supply chain a drag and drop question was used. The aim of the question is to receive a ranking of the complexity of the different stages in order to better interpret and understand the results. According to the results of the questionnaire (60 mentions) the construction site is the most complex area of all named. The second most complex area was identified as between the module manufacturer and the construction site, more specifically the logistics between them (33 mentions). The third position is located between the supplier and the module manufacturer (34 mentions) and the least complex area was identified within the production of the modules (54 mentions).

In order to determine the complexity drivers in each material flow section the variables with the highest means are chosen and analyzed with the use of correlation matrixes. In the first stage of the supply chain the variable "supplier's willingness to take responsibility for additional processes" ($\overline{x}$ = 3.71) showed the highest implication within the complexity of a supply chain in the modular housing industry. In the second section within the module production the variable "range of special requests" ($\overline{x}$ = 4.12) has the highest impact. This is also the case for the variable "size and weight of modules shipped" ($\overline{x}$ = 3.93) within the third section, between the module manufacturer and the construction site, as well as the variable "grade of infrastructure preparations on site (water, power)" ($\overline{x}$ = 3.64) in the fourth section (Table 1). For further research and the development of a supply chain management concept for the value chain in the prefabrication sector the complexity needs to be controlled. By knowing the variables with the greatest impact on complexity in the value chain, they can be explicitly taken into account when developing the supply chain management concept. By mastering these issues, the objectives of cost, time, and quality across the entire value chain can be met. Interestingly each of the four variables has a direct impact on the other areas of the supply chain which will be described below.

Table 1. Mean scores from the complexity drivers regarding the material flow

	(N=100)	Mean	standard deviation
Between the supplier and the module manufacturer	Number of suppliers	2.78	1.12
	Delivery times and reliability of suppliers	3.04	1.13
	Kind of delivery process (just-in-time, just-in-sequence)	2.63	.98
	Supplier's willingness to take responsibility for additional processes	3.71	.89
Within the module production	Grade of automation in manufacturing process	2.87	1.20
	Steadiness of production schedules	2.78	1.01
	Volume of manual production steps (plumbing and cabling)	3.43	.92
	Range of special requests	4.12	1.02
Between the module manufacturer and the construction site	Delivery times and reliability of carrier	2.49	1.16
	Size and weight of modules shipped	3.93	1.03
	Quality of infrastructure of the last transportation mile	3.39	.81
	Kind of delivery process (just-in-time, just-in-sequence)	2.62	1.05
Construction site	Delivery times and reliability of subcontractor	3.24	1.25
	Grade of infrastructure preparations on site (water, power)	3.64	1.07
	Type and volume of interior fittings	3.30	1.18
	Difficulty for module mounting process	2.59	.95

In a correlation analysis, the variables were evaluated with the remaining parameters from the material flow. From the results of the correlation table, only values with a correlation level of .01 (2-sided) are taken into account and assessed as significant (Appendix). The first variable "supplier's willingness to take responsibility for additional processes" shows a significant correlation with the parameters "volume of manual production steps (plumbing and cabling)" (.460**), "range of special requests" (.518**), "size and weight of modules shipped" (.298**), "quality of infrastructure of the last transportation mile" (.282**), "grade of infrastructure preparations on site (water, power) (.462**) and "type and volume of interior fittings" (.624**). Within the module production the variable "range of special request" has the highest impact in the complexity of the supply chain. In the correlation analysis, this variable has a significant correlation with the parameters "size and weight of modules shipped" (.491**), "quality of infrastructure of the last transportation mile" (.439**) as well as the parameters "grade of infrastructure preparations on site (water, power) (.393**) and "type and volume of interior fittings" (.577**). In the third variable with the highest impact on the complexity of the supply chain the correlation analysis shows that there is a significant correlation with the variable "quality of infrastructure of the last transportation mile" (.535**), "delivery times and reliability of subcontractor" (-.286**), "grade of infrastructure preparations on site (water, power) (.547**) and "type and volume of interior fittings" (.360**). The highest ranked parameter on the construction site is the variable "grade of infrastructure preparations on site (water, power)" which has a significant correlation with the variable "type and volume of interior fittings" (.529**).

4. Conclusion and Further Research

In order to achieve the predefined goals using prefabrication of house modules, a stable organizational structure throughout the whole supply chain is necessary (Wood & Ellis, 2005). The results of this study are limited to the area of specific stakeholders like architects, planners, engineers and general contractors involved in the supply chain of prefabricated housing modules. Furthermore, only the material flow in the supply chain was analyzed. Nonetheless the study is able to provide a platform for further research regarding the traditional construction industry.

A thorough and well organized supply chain management is an important aspect in every industry. This is also the case in the construction industry, especially regarding the prefabrication of house modules. This is because of the special characteristics of the prefabrication industry. In this case the construction site is the bottle neck of the whole process. The results of the survey show that in order to optimize the process, the degree of infrastructure preparations on site like the foundation and the water and power supply are the most critical ones. To achieve a continuous order process in order to match the goals, an unfinished construction site will delay the whole construction process as well as increase the costs for logistics and storage areas in the production. In order to quickly assemble the house on site, the interfaces between the other parties who are also involved must be uniform. This means that the way of communication must be standardized. One solution to tackle this problem is the use of the Building Information Modeling concept. According to BIM all involved parties have access to a uniform data model and thus always have the latest information on the current construction project (Bernstein; Gudgel & Russo, 2011). This means that besides the architects also the suppliers need to be involved and therefore must increase their competences and take more responsibility in the area of product development and production. In order to increase the competence of the supplier within the supply chain and by doing so to guarantee the successful finishing of the building project, the implementation of a supply chain management needs to consider the above mentioned aspects. On the construction site itself, finishing the buildings interior is also a relevant complexity driver in the entire process. It must be noted that although a large proportion of the work has already been completed during the prefabrication process, specific work steps such as closing the joints in the bathroom or kitchen can only be carried out on the construction site. These work steps have to be completed at the final destination of the modules, as damage may occur during transportation.

As a result, the quality of the transportation routes from the factory to the construction site play a major role. The adherence of the prefabricated modules to weight and height relevant road traffic regulations is also very important. For the development of a supply chain management for the value chain of prefabricated modules these specific aspects are crucial for meeting time related goals efficiently in the construction process. This means that methods which will be used in the supply chain management need to be focused on the area of logistics from the module manufacturer to the construction site and guarantee the reliable delivery of the modules on site.

Besides the already mentioned aspects, special customer requests have also a high impact on the supply chain management of prefabricated houses. When the requests stem from a determined product portfolio the changes in the order process are plannable e.g. the choice of a particular bath module or façade elements. If the chosen special requests are not designated for the process planning, efforts are higher and the production as well as the assembly of

the modules on the construction site get much more complicated. The results also show that the weight and the height of the modules have an important effect on the complexity of the supply chain. Moreover, the weight and the length of the module have a direct impact on the transportation process from the module manufacturer to the construction site. An interesting result is also the impact of the last logistic mile on the construction site and the range of special requests regarding the modules. The explanation of this correlation between those two aspects is that logistics are an essential part of the supply chain for prefabricated houses. The logistics from the manufacturer to the construction site can significantly increase when the customer or owner of the house has special requests regarding the features of the modules. Regarding the reliability and the delivery process there is no positive correlation. Interestingly, the relationship between the supplier and the module producer as well as the factors within the production have a negative correlation to the factor of the size and weight of the modules. This can be explained by the fact that delays in these two phases do not endanger or influence the quality of transportation to the construction site. This means that, different from the traditional construction industry, cross-company control, in this case the supply chain management, must act in order to ensure the smooth cooperation during construction projects. The complexity drivers who are assessed in this work thus have a direct influence on the corresponding organizational design, information management and the use of specific methods.

The previously mentioned correlation table shows the quantified context in the different areas of the value chain, which have an influence on the supply chain management in the modular housing construction. In subsequent research, the correlations should be specified more detailed and further empirically examined. A regression analysis should also be applied in order to model the relationships between the different variables. Besides the current results for the material flow regarding its impact on the complexity, further research could include the information flow into the analyses spectrum as well as new impact factors regarding the information flow. In order to finalize the supply chain management design, further specific research must be carried out in relation to the analyzed complexity drivers. Nonetheless, the results of this research paper pose the basis for being able to further develop a specific and well-coordinated supply chain management for the value chain of prefabricated modules.

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Appendix. Correlation table – complexity driver – supply chain of prefabrication of houses

		A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4
Number of suppliers (A1)	Correlation	1	.493**	.447**	.188	.046	.401**	.141	.138	.479**	-.083	.069	.432**	.175	.001	.234*	.423**
	Significance (two-part)		.000	.000	.061	.651	.000	.163	.171	.000	.409	.498	.000	.082	.995	.019	.000
	N	100	100	100	100	100	100	100	100	100	100	98	100	100	100	100	100
Delivery times and reliability of suppliers (A2)	Correlation		1	.598**	.152	.473**	.610**	.226*	-.092	.727**	-.216*	-.255*	.558**	.553**	.062	.090	.588**
	Significance (two-part)			.000	.130	.000	.000	.024	.361	.000	.031	.011	.000	.000	.538	.374	.000
	N		100	100	100	100	100	100	100	100	100	98	100	100	100	100	100
Kind of delivery process (just-in-time, just-in-sequence) (A3)	Correlation			1	.096	.104	.528**	.133	.015	.543**	-.206*	-.126	.704**	.337**	-.032	.158	.570**
	Significance (two-part)				.344	.302	.000	.188	.886	.000	.039	.217	.000	.001	.752	.115	.000
	N			100	100	100	100	100	100	100	100	98	100	100	100	100	100
Supplier's willingness to take responsibility for additional processes (A4)	Correlation				1	-.120	.097	.460**	.518**	.129	.298**	.282**	.226*	-.128	.462**	.624**	.239*
	Significance (two-part)					.233	.339	.000	.000	.200	.003	.005	.024	.206	.000	.000	.017
	N				100	100	100	100	100	100	100	98	100	100	100	100	100
Grade of automation in manufacturing process (B1)	Correlation					1	.491**	-.004	-.284**	.459**	-.179	-.130	.128	.727**	.016	-.315**	.217*
	Significance (two-part)						.000	.971	.004	.000	.075	.202	.204	.000	.857	.001	.030
	N					100	100	100	100	100	100	98	100	100	100	100	100
Steadiness of production schedules (B2)	Correlation						1	.156	-.141	.740**	-.200*	-.107	.424**	.475**	.057	.022	.502**
	Significance (two-part)							.120	.162	.000	.046	.294	.000	.000	.574	.827	.000
	N						100	100	100	100	100	98	100	100	100	100	100
Volume of manual production steps (plumbing and cabling) (B3)	Correlation							1	.363**	.216*	.351**	.166	.253*	.050	.414**	.512**	.248*
	Significance (two-part)								.000	.031	.000	.103	.011	.623	.000	.000	.013
	N							100	100	100	100	98	100	100	100	100	100
Range of special requests (B4)	Correlation								1	-.136	.491**	.439**	-.004	-.222*	.393**	.577**	
	Significance (two-part)									.177	.000	.000	.967	.027	.000	.000	.925
	N								100	100	100	98	100	100	100	100	100
Delivery times and reliability of carrier (C1)	Correlation									1	-.183	-.094	.519**	.553**	.054	.113	.622**
	Significance (two-part)										.068	.357	.000	.000	.593	.261	.000
	N									100	100	98	100	100	100	100	100
Size and weight of modules shipped (C2)	Correlation										1	.535**	-.034	-.286**	.547**	.360**	-.050
	Significance (two-part)											.000	.735	.004	.000	.000	.620
	N										100	98	100	100	100	100	100
Quality of infrastructure of the last transportation mile (C3)	Correlation											1	-.032	-.226*	.394**	.264**	-.041
	Significance (two-part)												.755	.025	.000	.009	.687
	N											98	98	98	98	98	98
Kind of delivery process (just-in-time, just-in-sequence) (C4)	Correlation												1	.332**	.183	.142	.568**
	Significance (two-part)													.001	.069	.159	.000
	N												100	98	100	98	100
Delivery times and reliability of subcontractor (D1)	Correlation													1	-.124	-.277**	.295**
	Significance (two-part)														.219	.005	.003
	N													100	100	100	100
Grade of infrastructure preparations onsite (water, power) (D2)	Correlation														1	.529**	.191
	Significance (two-part)															.000	.058
	N														100	100	100
Type and volume of interior fittings (D3)	Correlation															1	.291**
	Significance (two-part)																.003
	N															100	100
Difficulty for module mounting process (D4)	Correlation																1
	Significance (two-part)																
	N																100

** The correlation is significant at 1%. * The correlation is significant at 5%. Source: Prepared based on results of SPSS.