Linking product modularity to supply chain integration in the construction and shipbuilding industries

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Modularity is gaining relevance within Engineer-to-Order (ETO) industries such as construction and shipbuilding. So far, however, the concept of modularity does not seem to have fully captured all the facets within these specific industries. Yet, the impact of product modularity on Supply Chain (SC) integration is still an open issue. We investigated the concept of modularity within the ETO industry, by means of an explorative case studies approach. Some observations have allowed us to clarify the meaning of modularity within the ETO industry. Moreover, the relationship between modularity and SC integration has been examined, and a number of contingent variables – e.g. customization, IP awareness, innovativeness, company and product size – have been identified. These variables are able to affect the level of both product modularity and SC integration. The highlighted relations build a basis for further research steps using survey-related instruments.

Keywords:
Modularity
Supply chain
Construction
Shipbuilding

1. Introduction

Construction and shipbuilding industries are mostly local and highly volatile (Segerstedt and Olofsson, 2010). However, these industries are also widely recognized among the sectors that are able to contribute most to the growth of Gross Domestic Product (GDP) in many countries, even very diversely (see e.g. Sambasivan and Soon, 2007; Ortiz et al., 2009; Jiang et al., 2013), depending on the given country. Moreover, despite the severe economic crisis that has plagued many developed countries since 2008, the Bureau of Economic Analysis of (BEA) of the US Department of Commerce highlights that, over the years 1997–2013, the construction industry (not including satellite activities) accounted on average for 4.3% of GDP and 4.9% of full-time and part-time employees (BEA, 2014).

Furthermore, since 1996, the seminal study carried out by the Civil Engineering Research Foundation has recommended client-oriented flexible engineering to improve industry efficiency. CERF quoted modularity as a means to get at the same time an improved functionality of the building for user operations and an increased speed of building production, changes and renewal, claiming that the potential decrease in building time would be about 50% or even up to 75% (CERF, 1996).

Indeed, modularity is an approach to product design based on product breakdown and standardization (Ulrich, 1995). In make-to-stock or assemble-to-order industries, as well as in services, modularity has well-known advantages, i.e. it allows for flexibility, mass customization, cost reduction and control for variety (Browning, 2001; Brun and Pero, 2012; De Blok et al., 2013). Recently, modularity has also increasingly gained relevance within Engineer-To-Order (ETO) industries such as construction and shipbuilding, motivated by its impact on Supply Chain (SC) performance, in terms of lead-time (Voordijk et al., 2006; Pan et al., 2008), quality (Barlow et al., 2003), and cost (Barlow and Ozaki, 2005). While conventional definitions of modularity (e.g. Ulrich, 1995; Pine, 1999) seem to be unable to capture the specific facets of modularity within ETO industries, on the other hand, some other pragmatic definitions of modularity that can be found within the house building sector (Gibb and Isack, 2003), are hard to generalize.

To gain the full benefits of modularity, Pero et al. (2010) advocated that SC management should be aligned to product design. However, there is a lack of literature investigating the impact of product modularity on SC management within ETO industries (Doran, 2003; Doran and Giannakis, 2011), although the importance of SC integration to achieve modularity in the house-building sector is highlighted by scholars such as Hofman et al. (2009). Two schools of thoughts can be identified about the impact of modularity on SC

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integration. Fine (1998) claims that modular product design calls for loosely coupled SCs, whilst Doran (2004) maintains the opposite view. This dichotomy has been partially solved by considering other contingent variables like innovativeness (Caridi et al., 2012), however the relation between modularity and SC integration has not been tackled in ETO industries (Gosling and Naim, 2009; O'Brien et al., 2009; Benton and McHenry, 2010; Gosling et al., 2012).

Therefore, the objective of this research lies in investigating the concept of modularity within ETO sectors, particularly focusing on the construction and shipbuilding industries. The goal is to cast light on the relationship between modularity and SC management, mainly in terms of collaboration and information—sharing between SC partners.

The remainder of the paper is organized as follows. First, relevant literature is reviewed and the gaps in research are highlighted, so to refine the research questions (see Section 3). Our main results of several explorative case studies are summarized in Section 4: the insights of our observations lead to a redefinition of the modularity concept in the ETO industry (Section 5). Specifically, the relation between modularity and SC integration is discussed, some contin-gent variables are introduced, and the impact on costs and benefits is assessed. Section 5 reports on concluding remarks and outlines further fruitful avenues of research.

2. Literature review

2.1. Modularity and SC integration

Over the last two decades, modularity has attracted the attention of both academicians and practitioners in the broad field of management, which has generated a number of different definitions and indexes to measure it. Campagnolo and Camuffo (2010) look at modularity as a design principle and they go further along the path suggested by Hofman et al. (2009) in that they highlight the need to align modular product architectures and SC relation-ships, intended as multiple customer–supplier relationships. This paper also benefits from the work of Ulku and Schmidt (2011), who studied the link between product architecture (in terms of the extent to which a product is modular) and SC integration (i.e. whether the product development is done internally by the manufacturer or in collaboration with suppliers). Indeed SC integration refers to collaborative relationships based on information sharing along the SC (Bowersox and Daugherty, 1995; Caridi et al., 2006; Cigolini and Rossi, 2008; Bankvall et al., 2010; Eriksson, 2010; Lönngren et al., 2010; Reis et al., 2014).

The topic of SC integration through collaboration has received relevant attention by quite a number of authors over many years, and it has been measured according to many diverse indexes. Bowersox and Daugherty (1995), later followed by Handfield and Nichols (1999) focused on Information Technologies (IT) and data exchange, and studied the integration between information systems to share data (e.g. BIM—Building Information Modeling, CAD, ERP, CRM databases etc.), while Fine (1998) referred to the geographical proximity between a given company and its suppliers. On the other hand, Fine (1998) focused also on the content of transactions (i.e. components, whole modules etc.), later followed by Frohlich and Westbrook (2001), Droge et al. (2004) and Pryke (2004).

Finally, the seminal work of Fine (1998) also addressed the role of suppliers, by considering their involvement in the phases of building and/or ship development (measured e.g. in terms of number of meetings). This path has been further developed by Voordijk et al. (2006), Petersen et al. (2005) and by Brun and Pero (2012) and is linked to the work of Doran (2004) and Lau et al. (2007), who studied the control level of suppliers' activities during construction. The role of suppliers has been deepened by Lau et al. (2011), followed by Ro et al. (2007) who focused on long-term relationships with suppliers, measured in terms of years of collaboration between the company and suppliers and the level of trust among them.

A different school of thoughts in this field has been initiated by Lau et al. (2007), later developed by Caridi et al. (2012) and Droge et al. (2012). These authors direct their attention to the involvement of customers in a given SC.

2.2. Modularity and SC integration at the design stage

There seems to be no consensus on the impact of modularity on SC integration at the design stage (Caridi et al., 2012). The literature related to the implications of modularity on SC manage-ment within ETO industries shows disagreement among authors. For example, Vrijhoef and Koskela (2000) claimed that modularity in construction industries has an impact on the roles and responsibilities along the SC, which calls for stronger relationships among SC partners. This also seems to be confirmed in the field of transshipment (Cigolini and Rossi, 2010; Cigolini et al., 2013a,b). In this area, contractors should improve relationships with both off-site and on-site suppliers. They should promote the use of pre-cast, allowing many concurrent activities, and improving both information exchange and visibility along the SC. Doran and Giannakis (2011) later highlighted that modularity tends to reduce the need for strong client–supplier relationships, because you can craft the modules separately and then assemble them in the yard.

In the early days of this debate, Pryke (2004) suggested managing the entire SC by creating clusters of suppliers able to operate independently, thus providing a specific sub-assembly. Later, Chryssolouris et al. (2004) pointed out that shipbuilding requires tight coordination and continuous data interchange between suppliers.

2.3. Product modularity in the construction and shipbuilding industries

The use of modularity in the specific industry of construction can be traced back to wooden houses in Northern Europe. Yet, the real turning point seems to be in Japan. Toyota practices and lean-thinking principles are embedded in the process of house building: examples include Toyota Home, Sekisui Heim and Sekisui House (Gann, 1996; Barlow et al., 2003; Barlow and Ozaki, 2005; Jaillon and Poon, 2008). Beyond Japan, the interest towards modularity in ETO industries is rather loosely coupled with academic responses, as identified in the UK (Naim and Barlow, 2003; Pan et al., 2008; Gibb and Isack, 2003; Doran and Giannakis, 2011), Central Europe (Björnfot, 2004; Hofman et al., 2009; Schoenwitz et al., 2012) and the US (Quale et al., 2012).

The most widespread definitions of modularity in construction industry have been proposed by Adebayo et al. (2006) and Gibb and Isack (2003). Both teams of authors identified modularity with pre-fabrication (see also Castellano and Cigolini, 2002) and proposed a classification scheme of pre-fabricated modules. Indeed, both factory-made items and those never considered for on-site production are termed as component manufacture subassemblies. Pre-assembled units, which do not enclose usable space (e.g. timber roof trusses), are considered as non-volumetric pre-assemblies. Pre-assembled units that enclose usable space and are typically fully factory-finished internally, but do not form the buildings structure (e.g. toilet and bathroom pods) are named volumetric pre-assemblies. Pre-assembled volumetric units that also form the actual structure and fabric of the building (e.g. jail cells or hotel/motel rooms) are called modular buildings.

Mohamad et al. (2013) noticed that the standardization of work as an essential principle of lean management aims to improve the production process in construction. They introduced a design strategy – based on modularization and standardization – which aims to reduce the variety of building components, where this variety affects productivity negatively. These authors concluded that modularization improves the potential for standardization in one-off projects, but it should be applied early in design and in an integrated team to identify customer value trade-offs.

Finally, the use of modularity is also specifically reported in the shipbuilding industry Park et al. 1996; Kolić et al., 2010; Lee et al., 2013; Halse, 2014) as an instrument to cope with high competition and over-capacity.

In this area, Seubert (1988) early stated that the techniques of modular shipbuilding based on the Product Work Breakdown are very useful for the construction of light water reactor nuclear power plants. Later, Gockowski (2005) reported some experiences in the field of ship equipment coming from Polish and Northern Europe shipyards. He noticed a frequent use of big and richly equipped modules: e.g. in the case of the fuel booster block, shipyards tend to buy ready modules, which makes critical the cooperation between shipyards and co-operating firms, because these firms make more and more “ships parts”.

From a different angle, Granderson (2007) noticed that the modular ship construction process results in an extremely dynamic work environment, where the job site continually changes. This pushes the industry to find ways to mitigate the exposure to special hazards for employees working in a modular yard: one of the unique hazards facing the shipbuilding industry involves employees working near or under a suspended load.

More recently, Garver and Edyvane (2010) noticed that the implementation of modularity in Navy combatant design and construction could reduce overall ship acquisition and operational costs by introducing cost-saving process improvements. These authors quoted some studies over 30 years conducted by the U.S. Navy, and the implementation experience of foreign shipbuilders: it seems that reductions in construction costs of 5–10% are achievable. Rubeša et al. (2011) went further and they recognized that the shipbuilding industry plays an important role in increasing employment and productivity, especially when the market has fallen due to the influence of the global economic crisis. They introduced the modular outfitting concepts with the aim of optimizing the shipbuilding production process by increasing the portion of modular vessel outfitting as a way of shortening the duration of the shipbuilding process, reducing costs and increasing competitiveness without investing in new facilities, machines and tools.

Agarwala (2014) concluded that the concept of shipbuilding has shifted away from the traditional method where ships were constructed on a slipway: modular construction has proved to be the most cost effective way to deliver modern warships. Integration of modules means that only one major site is needed to assemble the various parts of the ship that have been constructed elsewhere. This trend toward building a ship using modules has dramatically changed the dynamics of shipbuilding.

Finally, Hunt (2014) identified cost reduction during refits and modernization as the primary motivator in early modular shipbuilding efforts and he forecasted ship capabilities increasing as future technologies combine with existing functions into smaller and lighter packages. He concluded by emphasizing that for modularization to be successful, design goals and requirements must be identified early in the design process and that modularization design principles must also be actively embraced and not only by ship designers but by system developers.

3. Research framework and research questions

3.1. Product modularity

Since product modularity is expected to be relevant in determining SC integration, products can be categorized according to the following taxonomy, rooted in the taxonomies developed by Gibb and Isack (2003) and Adebayo et al. (2006).

First, full modular products are those products where pre-assembled volumetric units form the building’s structure and fabric: modules are fully factory-furnished and then transported onto site (to the yard) and assembled.

Second, pre-assembled products are those products where pre-assembled units (either enclosing or not enclosing usable space) are not typically fully factory-finished and they do not form the entire building’s structure: modules are manufactured off site and then assembled on site.

Finally, traditional (non-modular) products are those products mainly composed of single items (instead of pre-assembled units) assembled on site to obtain the finished building: bricks cemented together on site with mortar represent the typical example in the house-building industry.

3.2. SC integration

SC integration (see e.g. Cigolini et al., 2011, 2014) should consider both suppliers (upstream levels) and customers (downstream levels). However, according to Fine (1998) loosely coupled and integrated SCs are to be differentiated and an intermediate level (Collins et al. 1997; Vrijhoef and Koskela, 2000; Voordijk et al., 2006; Caridi et al., 2012) added, so that the following taxonomy of SC integration in the ETO industry can be introduced.

First, loosely coupled SCs are those SCs where different actors have very limited interactions and suppliers (loose links between players). Suppliers might be geographically spread and usually they are neither involved in the design phase nor do they interact regularly; main contractors occasionally purchase off-the-shelf materials from a catalogue (Voordijk et al., 2006).

Second, modular SCs are made up from groups of suppliers so that there is tight integration among the players of each group (usually to provide some specific subassemblies), and low integration between groups (Droge et al., 2004). Here, strengthening the relationships between suppliers results in neither higher efficiency nor effectiveness (Pryke, 2004).

Finally, integrated SCs are those SCs where all the players are directly engaged and work closely with each other across the product life cycle, from the design phase to final execution. Usually, a supervisor is in charge of monitoring the progress of the whole work. An integrated SC abides by the four laws of integration: geographical, cultural, language and electronic proxi-mity (Fine, 1998).

Based on the definition provided for each SC integration level, and in line with the literature review, we have identified a set of parameters to measure SC integration. These parameters have subsequently been adapted to match the main features of ETO industries. Table 1 presents the list of parameters along with their definition. As for the content of the transaction, (i.e. what the company buys from suppliers) when suppliers are providing subassemblies, the SC is considered to be less integrated.

3.3. Contingent variables

This study supports the idea that certain contingent variables are likely to affect product modularity, SC integration, and their mutual relationships. Contingent variables represent some environmental variables, and/or sources of variance (or even disturbances) that are able to shape the managers’ decisions in terms of SC integration and/or modularity.

The full list of contingent variables considered here is given below.

Table 1
Parameters to measure SC integration.

SC Integration feature	Definition	References in literature
IT integrated systems and information/data interchange	The level of integration between information systems to share data, e.g. BIM, CAD, ERP, dedicated mail and databases, CRM database	Bowersox and Daugherty (1995), Handfield and Nichols (1999)
Suppliers monitoring during production and assembly phases	Level of control over suppliers' activities during construction	Doran (2004), Lau et al. (2007)
Supplier involvement in design	Degree of suppliers' involvement in the phases of building/ship development (e.g. number of meetings)	Fine (1998), Voordijk et al. (2006), Brun and Pero (2012), Petersen et al. (2005)
Customer involvement in the whole product	Level of customer's involvement the in the phases of building/ship development (e.g. number of meetings)	Lau et al. (2007), Caridi et al. (2012), Droge et al. (2012)
Long-term relationship with suppliers	Years of collaboration between the company and suppliers, and level of trust among them	Lau et al. (2011), Ro et al. (2007)
Content of the transaction	Purchased objects: whole module, subassembly, components	Fine (1998), Frohlich and Westbrook (2001), Droge et al. (2004), Pryke (2004)
Geographical proximity	Geographical distance between the company and its suppliers	Fine (1998)

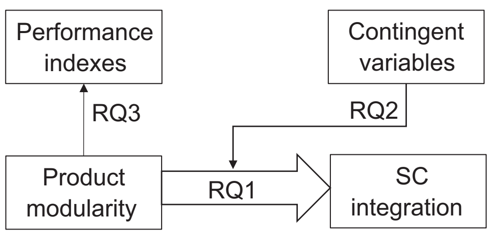

Fig. 1. Research framework.

1. Customization. This is measured as the degrees of freedom given to customers in defining product specifications. Products are typically structured in response to customer needs, where modularity reduces customization (Baldwin and Clark, 1997). Moreover, customization also drives SC integration (Pine, 1999), by enhancing product complexity and leading to required higher supplier/customer involvement (Fisher, 1997).
2. Innovativeness refers to product novelty for the company (Caridi et al., 2012; Lamberti and Pero, 2013). In some sectors other than ETO, innovativeness has been found to be relevant in determining SC integration (Caridi et al., 2012). Nevertheless, product development novelty is to be considered as a mediator factor (Dekkers et al., 2013): an innovative product might require higher SC integration, e.g. in terms of suppliers' monitoring in the yard. The employees are not skilled and the innovative modules have to fit the whole structure, thus requiring stronger monitoring (Duray et al., 2000; Jones et al., 2008).
3. Firm size. The larger the company, the more structured the network. Besides, large firms usually have more resources, e.g. plants to precast the modules (thus increasing product modularity) or integrated IT systems (thus increasing SC integration).
4. Product size, measured in terms of cost of the development. Bigger products are associated with higher managerial complexity, and more complex SCs.
5. IP protection, measured as the number of patented components in the product. IP awareness is linked to product modularity by means of reverse engineering: the higher the product modularity, the higher the opportunity to reverse the engineering process (Pryke, 2004). Speaking of ETO industries, the opportunity for IP rights infringements might stem from the capability of handling a given module.

3.4. *Performance indexes*

Some authors identified strengths and weaknesses of modularity as lead time compression (Gibb and Isack, 2003; Doran and Giannakis, 2011) and as reduced flexibility to changes in design (Gil and Tether, 2011; Cigolini and Rossi, 2010), even though flexibility is also connected to the management of suppliers (Gosling et al., 2012).

3.5. *Research questions*

To investigate the concept of modularity and its impact on SC integration within ETO industries, this paper is focused on the relations illustrated in Fig. 1.

To sum up this section, we pursued the following research questions:

RQ1 How does product modularity affect SC integration within the construction and shipbuilding industries?

RQ2 Which contingent variables affect the relationship between product modularity and SC integration?

RQ3 How does modularity in the construction and shipbuilding industries impact on performance?

This research provides several contributions: RQ1 aims to enrich the existing body of literature about the managerial implications of modularity within SCs in the construction and shipbuilding industries.

Since corporate decisions are expected to be affected by certain drivers, RQ2 aims to pinpoint key drivers and factors.

Finally, given the explorative nature of this study, RQ3 aims to identify a preliminary set of benefits and costs connected to the different types of product modularity within the construction and shipbuilding industries.

4. Methodology and overview of the case studies

4.1. *Methodology*

We employed an explorative case study approach to highlight how SCs are managed along a specific product development process. Typically, case studies are oriented at gaining an in-depth understanding of unexplored research fields, often in an effort to answer questions in the form of "how" and "why" (Yin, 1984; Eisenhardt, 1989) and to identify some contingency vari-ables that tell one case apart from the others.

For this purpose, we used the ETO approach to investigate five companies operating in different segments of the construction and shipbuilding industries. These companies collect their customers' requirements and develop the product from the design phase; they do not provide pure prefabricated buildings. According to Voss et al. (2002), this allowed us to delve into a rich set of experiences and contexts, able to provide a robust standpoint for observed similarities as well as the contingent factors potentially capable of explaining diversity. Multiple-case sampling helped increase confidence in the findings (Miles and Huberman, 1984) and support their external validity.

Cases were selected early on by using both the literal replication approach (therefore, e.g. cases with similar level of modularity have been picked) and the theoretical replication approach, with the aim of exploring different practices in terms of product modularity and SC integration (Yin, 1984). Indeed, literal replication led to choose cases with similar level of modularity (see Section 3.1), where similar results are expected, while theoretical replication led to choose cases with completely different levels of modularity, where contrasting results are expected.

The approach of this paper follows three steps. First, a well-structured search protocol, has been developed, whereby all the steps to follow in conducting the research were outlined and shared among all the research participants. The research protocol was organized in four sections: (i) introduction and main objectives of the study, (ii) main steps and procedures to follow, e.g. to contact the companies, procedures to gather and then store data and information, (iii) questionnaire, and (iv) case study report guidelines. Furthermore, a database has been set up, to store notes, documentation and further information.

Second, semi-structured interviews have been conducted, and a documentary analysis has been performed. To capture the relevant content and to cover all the topics of the questionnaire, each interviewee has been interviewed twice, each time for about four hours. In each interview, different parts of the questionnaire were discussed, and (when possible) additional information gathered on the questions discussed in the previous interview. Questions and answers were recorded and then transcribed.

Third, follow-up telephone calls were conducted, with some interviewees in order to check outcomes and gather missing data. For all five cases, additional information in the form of product documents (e.g. drawings and plans) and secondary sources (e.g. web content) was gathered. Table 2 summarizes the interviews details.

The unit of analysis was one specific product. Each interview was conducted by following a questionnaire (see details in Appendix 1). After a brief discussion on general information about the company, the interview focused on a successful product developed by the company. The structure of the questionnaire includes the following list of items.

1. General data about the company (employees, turnover, number of products developed per year, position in the SC).
2. Data about the interviewee (position in the company, experience).
3. Definition of the focus: a successful, highly representative product has been selected.
4. Product analysis. The selected product has been broken down, highlighting the main modules and the interfaces between them, to check whether they were specifically designed for one customer or if they were reused in other products and to check whether they were manufactured internally, outsourced or purchased from the market. Later the interviewee has been challenged to explain hurdles encountered in the design or the assembly phase of each module.
5. Product costs and benefits: product costs and actual delivery time (from customer request to final assembly) have been gathered.
6. Product drivers: the drivers that, according to the interviewee, mostly affect the product and why they are business-specific.
7. Customer: a general overview of the relationship with the customer is considered, to find out which parts of the product are more likely to be affected by the customer's decisions and which parts are completely managed by contractors.
8. SC structure: the overall structure of the SC has been assessed, mainly to check whether it is geographically spread and whether players are linked through long term relationships. Some reasonable information was collected about the way the SC owner coordinates suppliers and about the contribution of suppliers to the product management.
9. SC management, in terms of what practices are put in place during each different phase and why: critical phases were searched, since they require more coordination and since they are traditionally plagued by the highest number of mistakes.

Then, collected data was categorized and contextualized (see e.g. Miles and Huberman, 1984), to reveal any relationships between events and circumstances. To uncover the relationships between product modularity, SC integration and contingent variables, explanation-building procedures have been applied. These structured procedures for data collection and analysis, as well as the use of the semi-structured interview protocol, helped us enhance the reliability of our research (Yin,1984).

4.2. Overview of the case studies

Table 3 illustrates the five cases in the ETO industry, following the path described in Section 3 with reference to the SC integration features.

Case 1. refers to a hospital. This type of building is a traditional (non-modular) product, with only a few relevant pre-assembled modules (surgery rooms, façade, precast bathrooms, and mechanical systems). Product complexity prevents the use of many modular solutions for the building. The SC owner has a tight control on all the phases of the development, and directly manages all the suppliers. Most of the activities are carried out on-site (because of the low modularity) and site management is a

Table 2
Interviews details.

Case study	Data sources	Interviewee (s)	Number & time devoted to interviews [h]
Case 1	Interviews/Company visit /Website	Chief project manager + Purchasing manager	2 for each respondent/about 3.5 h each
Case 2	Direct interviews/Company visit/Website/Company documents (drawings, pictures)	Managing Director + Project manager	2 for each respondent/about 3.5 h each
Case 3	Direct interviews/Company visit/Website/Company documents (drawings, pictures)	Project manager + Designer	2 for each respondent/about 4 h each
Case 4	Direct interviews/Company visit/Website/Company documents (drawings, pictures)	Managing Director	2/about 4.5 h each
Case 5	Direct interviews/Company visit/Website/Company documents (drawings, pictures)	Designers of structure engineering and of mechanical equipment	2/about 4.5 h each

Table 3
Overview of the case studies.

Case study	Case 1	Case 2	Case 3	Case 4	Case 5
Company focus	Major public infrastructure	Architect studio, project design	Civil & industrial facilities, house building, systems for buildings	Wood structures, residential house	Project and shipyard
Position along the SC	SC owner, general contractor	Client	Design office, SC owner	Wood manufacturer, final assembler	Designer and final assembler
Turnover	€ 90 Million	€ 7.5 Million	€ 1 Million	€ 5.6 Million	€ 25 Million
Employees	150 on-site workers + 50 staff workers	45 employees + 15/20 on-call	11	48	> 200
Projects per year	< 1	3–4 (precast industry)	2–3 (house industry)	2–3 (precast industry)	3
Product	Hospital facilities	Modular houses	Four floors houses	Schools	Luxury boats
Product size	€ 85 Million	€ 900,000	€ 1.1 Million	€ 1.4 Million	€ 15 Million
Delivery LT	60 months	14 months	16 months	9 months	24 months

crucial issue: more than 150 people work together on-site during peak periods. Customization is rather high and all the innovative solutions are included in specific modules that are outsourced to core-skilled suppliers. The design phase is critical, requiring the collaboration of most suppliers to review the design. Reworks and in-yard solutions are daily activities. Integration with customer and suppliers is perceived as a vital practice to avoid and solve problems.

Case 2. refers to a full modular house. Delivery lead-time for this product is about 14 months; however, only 10 days are devoted to on-site assembly. Indeed, three floors are totally assembled off-site and then transported 70 km from the assembly plant to the site. The building is composed of two modules (living rooms and bedrooms), fully factory-furnished internally. Every detail of the entire product is defined at the design phase and the major efforts are in the design phase to avoid future reworks. The volume of the structure is a constraint for the customer, since both crane capacity and the required space for manoeuvring lead to transportation hurdles. The overall product benefits from a very short lead time and the highest possible quality. All the modules have been designed to be disassembled and moved elsewhere later. Both the suppliers and the customer are loosely coupled along the SC: standardized interfaces ensure no need for integration in most phases except in the design.

Case 3. refers to a four-floor house. Delivery lead-time is about 16 months; however, only 16 days are needed for on-site assembly. It is a kind of pre-assembled product because horizontal and vertical panels, composing the wood structure, are cut in the plant and then moved to the yard. The panels are kept as standardized as possible, to benefit from economies of scale within the manufacturing process and to avoid frequent changeovers. Where the interfaces between two modules are narrow (e.g. between the vertical pillars and the roof) suppliers are highly integrated – by means of meetings and common design reviews – so that they provide both modules (e.g. the vertical pillars and the roof). All the other modules are quite loosely coupled, leading to a more efficient SC: on-site lead-time is extremely compressed and crane utilization is lower than with traditional construction. The finishing phase is carried out on-site with no coordination between the wood structure supplier and the other players (heating suppliers, furniture suppliers etc.): here the quality level achieved in the plant manufacturing prevents mistakes. In the end, a significant effort is devoted to all the interfaces for design, pair and study purpose, but the effort is balanced by a reduced time devoted to managing relationships along the SC.

Case 4. refers to a school. Delivery lead-time of the product was about 9 months, only one of which (31 days) is required for assembly. Construction is mostly made by precast wood panels (similar to Case 3), even though the design of the structure is more complex due to less regular and more various shapes for each module. The differentiation in the design leads to less economies of scale. Indeed, the complexity requires a higher integration between suppliers in order to assess the critical parts of the building. Customer involvement is quite low at the beginning, but increases at the end of the construction, when decisions about internal furnishing and finishing take place. Suppliers are located in areas far from each other and all the relationships are loosely coupled without any IT-based integration or meetings between suppliers in charge of different modules. The product is split into three chunks: foundation, wood structure and internal systems & furnishing, without overlapping or connections among them, due to the loose connections between the modules. While the size is almost the same as Case 3, on-site lead-time is around two times larger, due to the greater complexity of the modules.

Case 5. refers to a luxury ship. The product is fully designed to customer specifications (i.e. 45 m long and 3 decks tall) except for a standardized frame of the hull dead-body. Key modules include the hull modules, upper walls, decks, internal living modules (kitchens, bathrooms, and service rooms), mechanical systems (engines, navigation, pumps, entertainment) and service systems (cooling, heating, water supply and anti-theft). The connections between these modules are quite tight and the assembly is effort-consuming. The SC owner usually tries to purchase as many standard modules as possible (in particular, systems and mechanical parts) to avoid the expense connected with customization. Occasionally, shipbuilders try to purchase the entire subassembly instead of each module one at a time: this approach shifts most of the bargaining power to the supplier; it also dramatically reduces product complexity. For very critical modules (e.g. hull and decks), integration with suppliers is very high, whilst for the more customized ones, major integration is with the customer. The SC management phase is critical in both the design and yard phases, with constraints related to the available space and a tight schedule for the yard occupation.

The case studies are summarized in Table 4, while more details can be found in Appendix 2.

5. Results

5.1. Redefining product modularity for the construction and shipbuilding industry

Our analysis of case studies led to the insight that the definitions of product modularity proposed in the literature seem to be

Table 4
SC integration features in the case studies.

Case study	Case 1	Case 2	Case 3	Case 4	Case 5
Product modularity	Traditional	Modular	Pre-assembled	Pre-assembled	Pre-assembled
Innovativeness	High	High	Low	High	High
Product customization	High	Low	Medium	Medium	High
IP awareness	High	Low	Low	None	High
IT systems and information/data exchange	High	Low	Low	Medium	Medium
Suppliers monitoring and relationship during manufacturing and assembly phase	High	Medium/low	Medium/Low	Medium/low	Medium/Low
Suppliers involvement in design	High	Medium	Medium/Low	High	High
Customer involvement	High	Low	Medium	Medium	Medium/high
Long term relationship with suppliers	Low	None	None	None	Medium
Content of the transaction	Simple elements	Mainly subassemblies	Subassemblies and simple elements	n.a.	Many items purchased as subassemblies
Geographical proximity	Relatively low	Relatively low	High	High	Low

insufficient to fully capture the complexity and particularities of ETO industries. For shipbuilding, each single module in a boat must be connected to the systems that contain it. This understanding has refined the definition of product modularity by adding the concept of systems embedded in the structure.

Indeed, Gibb and Isack (2003) provided some insight about the types of systems that fit every module. However, the authors differentiate between the various types of modularity only based on the structure. This makes their definition of modularity appropriate for Cases 2–4 (where the focus is totally upon the structure), but it fits neither Case 5 (ship) where parts like engines, cooling systems, pumps and other mechanical apparatus are stand-alone modules, nor Case 1 where some systems are embedded in the product.

For this reason, one finding of the case studies analysis performed within this research project lies in a set of three new definitions for product modularity in the construction and shipbuilding industries.

First, modular products are pre-assembled in volumetric units (fully factory furnished) that form the actual structure and fabric of the building, with mechanical and service systems embedded in the modules. External connections with pipes and canals must be realized on-site, with plugs settled in each module. A distinctive feature of the shipbuilding industry is in that this modularity refers to cargo boats, especially for the hull and the command cabin. Each section of the hull embeds a specific part of the mechanical systems, so that only the pipe connections have to be made in the yard. A specific case is the so-called “pop module”, where the entire engine and gear system are embedded. According to almost all the inter-views related to Case 5, this module is defined to avoid on-site operations to install the engine and gear system after assembling the other modules, which would result in great difficulties.

Second, pre-assembled products are mainly composed of either pre-assembled units that do not enclose usable space or pre-assembled units that enclose usable space and are not typically fully factory-finished internally. These pre-assembled units do not form the entire building structure. Mechanical and service systems can be embedded in some modules (e.g. pipes, canals) or they can be considered as stand-alone units plugged into the rest of the product. The systems can be either embedded into the modules, as under modular products (e.g. pipes embedded into the roof panels) or they can be treated as an external component of the structure as if they were modules (e.g. the heating system in Case 3). The systems that are not embedded in the structure are usually purchased as subassemblies, in a similar way to boilers, pumps and pipes of a heating system that brings water towards all the apartments of a building: by purchasing these elements together (instead of separately), you purchase the heating subassembly. In the shipbuilding industry, the engine subassembly is made up of the engine, the axial transmission and the fuel pumps from the fuel tanks.

Third, traditional (or non-modular) products are mainly composed of single items (not by pre-assembled units): e.g. the mechanical systems or internal equipment are considered as single items and never as a subassembly. The focus for the mechanical and service systems is the same as the overall structure: the structure is assembled on-site, with a few precast modules. The same happens for the systems, which are added to the structure through on-site operations. Within the construction industry, the heating system is constituted by boiler and water pumps: they are purchased separately but connected during the construction process. The same holds in shipbuilding: gears, axis and engine are purchased separately and then assembled on-site.

5.2. *The relationship between product modularity and SC integration*

The definition of product modularity (as refined above in Section 5.1) together with the level of SC integration (see Section 3) allows us to provide a preliminarily mapping of the case studies (see Fig. 2) along two dimensions: type of product modularity and supply chain integration.

As Fig. 2 suggests, we were able to group the case studies into three major clusters.

The first cluster refers to modular products and loosely coupled SCs. It corresponds to the top right corner of Fig. 2 (see Case 2). According to Droge et al. (2004), modularity is leveraged (after the initial design) to let all the suppliers work on their own modules separately and without any kind of information exchange, subject to deadline constraints. Coordination is granted by a clear definition and control of modules interfaces at the design stage: nearly all the activities are performed off-site, thus reducing delivery lead-time (and especially assembly lead-time), and making workforce manage-ment easier. Indeed the Managing Director of Case 2 stated: “the modules outsourcer comes to the yard and when all the modules are gathered to the site, he starts matching them with a crane and the game is done”. Furthermore, product modularity allows the workforce to work on most of the activities in parallel, and to overlap the production of different modules, which leads to a reduced product customizability.

The second cluster refers to traditional (non-modular) products and integrated SC. It corresponds to the bottom left corner of Fig. 2 (see Case 1). The assembly is essentially

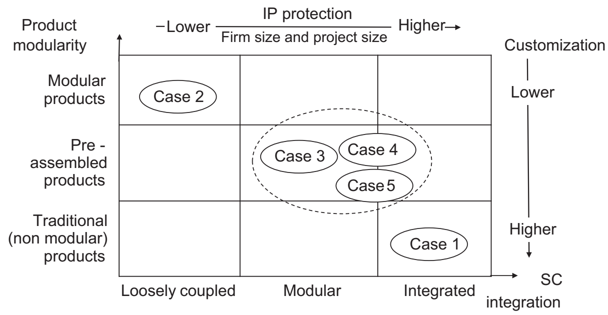

Fig. 2. The product modularity vs. SC integration matrix.

operated on-site, with many suppliers involved, each of them with its own workforce, under the control of the SC manager who experiences increased job complexity. Indeed, the General Manager of Case 1 stated: "during the worst time we have had 150 people on the yard plus cranes and trucks from each different outsourcer: it was a problem for safety and sometimes some technicians were waiting to get into the building and start working, because someone else was occupying the access area. That's a waste of time and, of course, the Gantt can't be respected if activities can't be perfectly parallelized". He also added: "project duration is significantly long, since you cannot overlap too many activities (even for the sake of safety)". Whereas the Purchasing Manager of Case 1 reported: "information exchange is critical", thus amplifying the impor-tance given to IT system and information exchange: e.g. to notify every single supplier about a change newly introduced into the product. Indeed, in Case 1, every lack of coordination between suppliers, led to rework of some parts, e.g. the mechanical transportation systems and the walls crafts.

The third cluster refers to pre-assembled products and modular SC. It corresponds to the center of Fig. 2 (see Cases 3–5). In particular, both Cases 4 and 5 have strong integration with some suppliers. In Case 4, during the design phase, the SC owner established a three-step review with the module suppli-ers, supported by a Building Information Modeling (BIM) soft-ware tool for information exchange. After the design phase, SC integration is limited (each supplier works on its own), with coordination only becoming relevant again during assembly phase. Here interfaces are quite tight, with a narrow pairing, and the customized shapes of the panels make each module different one to another, with specific settings. In a similar way, in Case 5 some critical suppliers are co-located and managed according to long-term partnerships, even though the SC owner tries to buy as many modular subassemblies as possible, to keep the maximum number of activities far away from the yard. In Case 5, the interfaces are not standard at all – which is a distinctive feature of the shipbuilding industry – so the need for module integration is quite high and it triggers the above-mentioned SC integration. Finally, in Case 5 the complexity of some modules prevents them from being managed as a standard product, and a sort of craftsmanship production is in place (e.g. special decks). On the other hand, Case 3 is an example of modular SC, because interactions are lacking between suppliers providing different macro modules (foundation, structure, inter-nal filling) due to standardized interfaces.

5.3. The impact of contingent variables

5.3.1. Product customization

By analyzing the differences among the cases, we examined contingent variables that might determine a certain level of product modularity and/or SC integration.

Pine (1999) noticed that modularity is a tool for economically developing customized products, by mixing and matching standard modules: this is the case of mass-market industries, such as the computer industry (e.g. Dell Company). However, in the case studies reported here, customization seems to be strongly connected to the customer involvement in the product, and appears to decrease as modularity increases (see Fig. 2): high product customization (Cases 1 and 5) is obtained by strongly involving customers all along all the phases of product design, manufacturing and assembly. Case 4's Managing Director summarizes the relevance of the relation between customization and customer involvement by saying: "customer involvement is the only way to reach customization". Indeed, customization is perceived as the degree of freedom given to customers any time along product development.

To provide customers with the opportunity to suggest changes in the product along each phase, products are designed to accommodate such changes, e.g. by reducing the level of standardization of modules and interfaces or by reducing prefabrication level, thus reducing product modularity. In Case 3, the number of independent modules was defined so as to reduce the number of interfaces between modules, together with the impacts on other modules by changes requested by the customer all along the development phases, while maximizing the opportunities for the customer to change each module. Moreover, flat modules guarantee the customer a certain degree of freedom to change specification along the manufacturing phase and even assembly, which would not be feasible with pre-assembled volumetric units. To balance costs and customization level, Case 5 differentiates modules according to the level of customization: only fully customizable modules can be changed along all stages of the development. Indeed, none of the Case 5 modules is a volumetric unit, which is another distinctive feature of the shipbuilding industry.

Barlow et al. (2003) noticed that, in the Japanese house building market, companies offer different levels of customization, and their SC model differs accordingly, ranging from make-to-order to make-to-stock. Make-to-stock policy allows limited cus-tomization and no significant input from the customer. Interest-ingly, a similar pattern can be observed also in Case 2, despite it being an ETO company performing all the activities from design to assembly following a customer order. In fact, the project manager of Case 2 stated: "our skill is to create shapes that may fit the requirements of prospective customers and use them multiple times in different projects: each project is still a one-of-a-kind structure, but it dramatically lowers the cost of re-design". Thus, the designers, leaving less room for customer choice, think about new modular solutions or reusing existing modules without contacting the customer: they gathered product requirements from the customer only at the beginning.

Based on the abovementioned results, we state the following propositions (to be investigated with further research):

Proposition 1. The higher the customization, the higher the customer involvement all along the development project.

Proposition 2. The higher the customer involvement all along the development project, the lower the product modularity.

These cases support the idea that customization leads also to SC integration: customization introduces complexity in the product and leads to higher involvement of both customers and suppliers. Indeed, to accommodate customer changes and so as to quickly react to customer request, higher information exchange and suppliers involvement in design is advisable. This is noticed particularly in the shipbuilding industry, as one of the interviewees of Case 5 (belonging to the shipbuilding industry) mentioned: "If the customer allows us to take some decisions on behalf of him, everything is much easier, but sometimes the client's decisions are so unusual that we have to coordinate more suppliers".

Based on these results, the following propositions can be formulated:

Proposition 3. The higher the product customization, the higher the SC integration.

5.3.2. *Innovativeness*

Innovativeness has a twofold meaning, whether it is referred to the product concept and architecture, or to technical and technological solutions implemented in each module.

Innovativeness at the modules stage seems to reduce product modularity. According to Duray et al. (2000) and to Jones et al. (2008), an innovative project is typically challenging to manage. In Case 2, technology innovation is achieved by acquiring the innovative modules from a global expert player and – to fit the innovative modules to the others – the interfaces and the other components are tailored and crafted on-site, thus reducing modularity. On the other hand, in line with Caridi et al. (2012) in the furniture industry, higher SC Integration is associated with higher modules innovativeness: e.g. in Case 5, innovative solutions for critical and non-customized parts are developed by well-known trustworthy suppliers and strongly integrated into the project SC, which is another distinctive feature of the shipbuilding industry. In Case 4, conjoint design between the two wood suppliers led to developing new technical solutions to manufacture the load-self-supported structure.

A U-shaped relationship between modularity and innovativeness has been found in the electronic industry (Lau et al., 2007). This study suggests that, in ETO industries, product modularity reduces modules innovativeness through SC Integration. Indeed, in Case 2, where the product is highly modular, there is no need for a deep, structured integration with suppliers (e.g. IT integration and data exchange) and subassemblies are purchased off-the-shelf: product innovativeness lies in the innovative design concept and in the solution for easily assembling the house. No innovative solutions were developed for one specific module, nor was it needed or feasible to exchange information with suppliers about possible innovative solutions. On the other hand, as mentioned above, where suppliers were involved in product design (i.e. Cases 1, 4 and 5 associated with lower modularity), modules innovativeness is higher.

These findings suggest a self-enhancing positive loop (see Fig. 3) between innovativeness, product modularity and SC inte-gration that might be triggered either by the need for some innovation in a product (see Case 2) or by SC partners – either customers or suppliers – as in Cases 4 and 5.

Based on the results above, we posit:

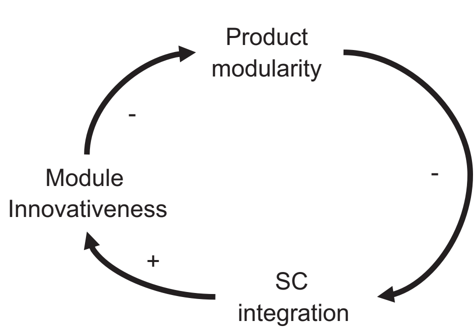

Fig. 3. The positive loop of innovation.

Proposition 4. The higher the modules innovativeness, the lower the product modularity

Proposition 5. The higher the SC integration, the higher the modules innovativeness

5.3.3. *Firm and product size*

It seems that companies can successfully handle modular and pre-assembled products, provided that: (i) they have a plant to build the modules, (ii) they rely on a network of suppliers providing the needed skills, and (iii) the size of the product is not too big. Indeed, product modularity, as defined above, is intimately connected to preassembly, so it requires high invest-ments in production plant and skills. In fact Cases 2, 4 and 5 reported that they needed to either create a company to manage the product either by acquiring another company (see Case 5) or by creating a new venture (see Cases 2 and 4). Based on these results, the following proposition can be formulated:

Proposition 6. The bigger the product size, the lower the product modularity, if the firm is small.

5.3.4. *IP awareness*

The role of IP awareness for decisions about product modularity seems relevant.

Four companies out of five in the sample have included patented modules or component in the product. Patented modules (whose patent is owned by the company) are included in the project design as standalone modules and preassembled by the patent owner, thus increasing product modularity (see Cases 1 and 5). Cases 2 and 3 inserted patent-protected technological solutions into the modules, with no effect on product modularity. Based on the findings above, we posit the following proposition:

Proposition 7. The higher the number of patented modules, the higher the product modularity.

5.4. *Impact of product modularity on performance indexes*

As far as lead-time and flexibility are concerned, case studies results suggest that delivering traditional (non-modular) products leads not only to a longer lead-time, but also to higher flexibility to design changes. This can be noticed by comparing Case 1 against the others. In particular, reducing the number of on-site activities is associated with a lower number of reworks, because of the high quality of the modules (according to Barlow et al., 2003). More-over, less modules improves the crane usage in the yard, which reduces the time needed to assemble the building or the ship in the yard. On the other hand, the more modular the product, the greater the effort spent in the design phase. In Case 2 a relevant amount of resources has been devoted to modules design, since any mistake at the design phase has a dramatic impact on production; due to this a rework on the yard is seldom feasible. In Case 5, interfaces between the modules were carefully designed to guarantee a minimum need of spending time in coordination activities and to allow for sourcing the modules to suppliers (e.g. for the hull and the upper tack). out This was achieved by setting a tight coordination between the involved suppliers from the beginning. Given the distinctive features of the shipbuilding industry, the time spent in designing interfaces was balanced by reduction of the assembly lead time.

In the electronics industry, modularity is meant to give higher flexibility to late changes in the product design (Sanchez and Mahoney, 1996). V*ice versa*, the results presented here suggest that modularity reduces the opportunity for late changes of the product during the design phase. This is in line with the results found about customization (see Section 5.3). As mentioned above, within ETO industries, higher product modularity is associated with higher levels of prefabrication, thus reducing the opportunity for the customer to ask for changes later in the product development. Therefore, we state:

Proposition 8. The higher the product modularity, the lower the project lead-time.

Proposition 9. The higher the product modularity, the lower the flexibility to changes late to the product design.

Different skills are required in the analyzed case studies, yielding different costs. E.g. in Case 1, all the activities are performed in the yard by many people, together with a higher skillset to manage them, whereas a modular project requires investments in production machinery and in training for designers, as well as ability to coordinate a wide set of modular suppliers. Finally, one of the major benefits of modularity is in the economies of scale at the production phase, particularly when the company is able to use the same module several times in different projects. Therefore, the following proposition is posited:

Proposition 10. The higher the product modularity, the lower the costs (per unit of time) of the building phase in the yard.

6. Conclusions

Our paper investigated the concept of modularity within the construction and shipbuilding industries. While analyzing and classifying the case studies developed through some interviews to company managers, the definition proposed by the literature was found to be incapable of fully capturing the complexity of both construction and shipbuilding at one time. Therefore, we first introduced a new set of definitions for product modularity.

Modular products are those products where pre-assembled volumetric units – fully factory furnished – also form the actual structure and fabric of the building. Pre-assembled products are mainly composed of pre-assembled units that do not form the entire building's structure. Traditional (non-modular) products are mainly composed of single items (not by pre-assembled units): the structure is assembled on site and the systems are added to the structure through on-site operations.

Next, the link between modularity and SC management has been analyzed, mainly in terms of collaboration and information sharing between SC partners with both suppliers and customers. Our case study results confirm the alignment proposed by Fine (1998), i.e. as product modularity increases, SC integration diminishes. In particular, the case studies led to identification of three main categories of products and SCs:(i) modular products with loosely coupled SCs, (ii) traditional (non-modular) products with integrated SC and (iii) pre-assembled products with modular SC. This confirmed Fine's thesis that the higher the product modularity, the lower the SC integration.

Moreover, the study presented in this paper supports the idea that some contingent variables are able to affect product modularity, SC integration and the relationships between them. Few variables are taken from the literature, like customization and project novelty for the company (referred as innovativeness). Some others are based on the industry structure, like firm size, product size and IP awareness (measured as the number of patented modules in the project).

By comparing the different cases, the contingent variables that might determine a given level of product modularity have been investigated. Customization and customer involvement play a role in reducing product modularity, while being associated with higher integrated SC. Small firms seem to rely less on modularity when the product is big. Interestingly, SC integration seems to foster module innovativeness. That, in turn, is associated with lower product modularity. Finally, IP awareness plays a relevant role in steering decisions about product modularity: the higher the IP awareness, the higher the product modularity.

Finally, modularity has a positive impact on SC performance: our results suggest that traditional (non-modular) products are connected to longer lead-times, but also to higher flexibility to changes in design. However, a modular project requires investments in production machinery and in training for desi-gners, as well as ability to coordinate a wide set of mod-ular suppliers. In turn, production machinery allows economies

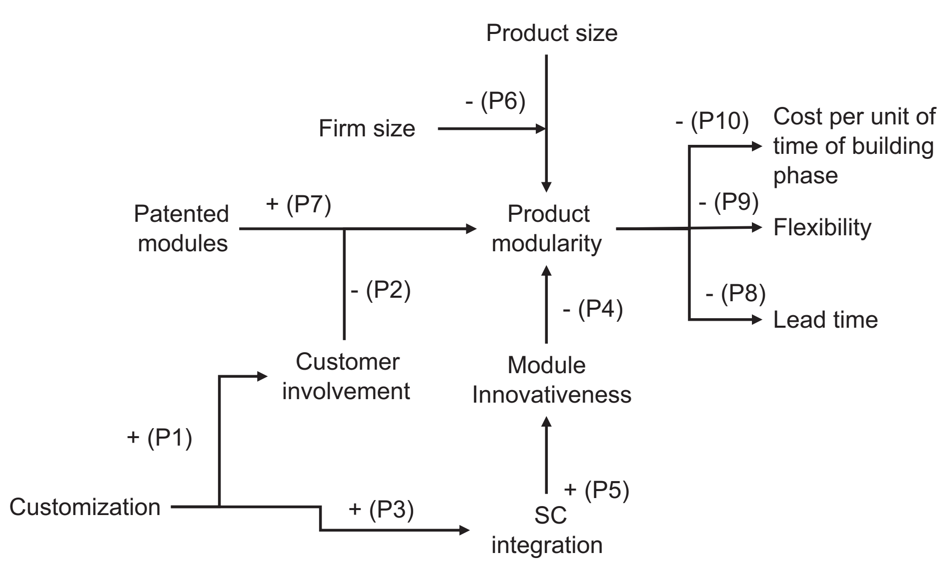

Fig. 4. Overview of the propositions identified.

of scale at the production phase, particularly when the company is able to use the same module several times in different projects.

Results have been summarized in ten propositions. Fig. 4 depicts the complete overview of the propositions.

The discussion above (further supported by Benton and McHenry, 2010) leads to the conclusion that SC managers in the construction and shipbuilding industries should evolve so to be in control of the SC as a whole rather than as a sum of independent relationships. This means that they should deal with organization-related issues to coordinate subcontractors, material suppliers and information within the SC, to deliver satisfaction to the ultimate client.

Ideally, SC integration should represent a win-win goal of circular benefits, as outlined in Fig. 3, where modularity enables integration, which is the key to achieving innovativeness. In this way, each company in the SC obtains its own profitability and success by creating customer value, while at the same time reducing its own costs and increasing its performance, thereby enabling the SC to deliver value to the client. The satisfied client in turn rewards the SC with loyal contracting power, allowing profitability to be transferred back down throughout the SC itself, which – in turn – fosters further SC integration.

Future research will be devoted to test the propositions with a large-scale survey in the shipbuilding and construction sectors. The survey aims at providing stronger support to the propositions, and at highlighting other relationships between the variables, as well as other relevant differences between the two sectors. More-over, a specific focus will be devoted to investigate and quantify the impact on the performance of time, cost and flexibility of the adoption of modularity.

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Appendix 1. The questionnaire used in case studies

1. Company (Name, Turnover, Number of employees, Position in the SC, Number of project in a year, Core business).
2. Interviewee (Position, Experience, Focus).
3. Select a successful project in which you participated that represents most of the business of your company.
4. Project analysis.
   - Describe the main output of the project, i.e. the product.
   - Can you decompose the project output in macro subassemblies? How?
   - Are those subassemblies further decomposable in smaller modules?
   - Are those modules reused across projects or were designed for this specific project?
   - How are these modules interfaced with the others? Are those connections tight?
   - What hurdles do you usually face when you assemble those modules? In your opinion, why?
   - Are those modules either internally manufactured or outsourced to a specific supplier or purchased on the market?
   - Is there any patented module in the product? If so, how many? How did you manage them?
   - Do you define the product as innovative? Why?
   - Do you define the product as customized? Why?
   - How do you think the external environment where you operate can affect your product?
   - What are the delivery lead-time and the cost of the project?
5. Customer
   - Who were the customers of the project?
   - What is their role in project?
   - How do you get in touch with them? Do you plan a given number of meetings or they are fully embedded in the project?
   - In which phases they have the most influence?
   - How will you act if the customer proposes a late change in the project?
   - How do you cope with very specific and customized solutions required by the customer?
   - Are there long term relationships in place with the customer?
   - What practices do you put in place to avoid errors, misunderstandings or late changes?
6. Project management:
   - How do you take part to the project? What is your role.
   - How is the project structured (e.g. deadline, schedule, penalties)?
   - How can the project be decomposed in phases?
   - Which are the most critical phases? Where do you most spend time?
   - What is the role of the project owner? How tight is his control on all the phases?
   - How do you cope with difficulties?
   - What strategies and practices are put in place in each phase to offset the criticalities?
   - How are those practices related to modularity?
   - How are those practices related to your suppliers' involvement?
7. Supply chain structure:
   - Which suppliers were involved in the project?
   - Where are your suppliers located?
   - How do you get in touch with them? How many meetings do you arrange?
   - What is their control on the project? How much are they relevant?
   - Do you have any IT system to exchange information?
   - Have you any long-term relationship with your suppliers? In what other projects have you collaborated?
   - Do your suppliers meet the customer?
   - Do they take part to the design phase? How?
   - Is there any joint venture with them? How do you usually share benefits?
   - How do you coordinate whit them if a problem occur?
   - What strategies and practices are put in place in each phase, to offset the criticalities?
   - How are those practices related with the modularity?
   - How are those practices related with your suppliers' involvement?

Appendix 2

See Table A1.

Table A1
Summary of the cases (multiple pages).

Case	Case 1	Case 2	Case 3	Case 4	Case 5
Modularity	Traditional product	Modular product	Pre-assembled product	Pre-assembled product	Pre-assembled product
Innovativeness	High: complex and innovative solutions for the systems embedded in the product	High: new concept and new solutions studied to make the assembly easier	Low: most technological solutions are already used abroad	High: new technical solutions to make the load-self-supported structure	High: new technological solutions developed for the product (materials and design)
Customization	High: specific modules and the overall building's design are highly customizable	Low: size and dimensions are constrained, and one module (living) is totally given	Medium: some degrees of freedom are given to customer	Medium: customers can customize the building with some constraints (shape & size)	High: customers can choose each feature of the ship
IP awareness	High: façade connections are patented (patent owned)	Low: X-Lam panels are patented (not owned)	Low: solutions for hooks are patented (not owned)	None	High: hull design and deck vertical walls connection are patented (patent owned)
IT systems and information/ data interchange	High: BIM, CAD, ERP, dedicated mail, database, etc. Good information exchange avoids problems	Low: absent between suppliers	Low: used only to exchange data in the design phase	Medium: BIM, CAD and common database are implemented between the two NewCo members	Medium: used for information exchange, design and CAD documents and schedule updating
Suppliers monitoring and relationship during production and assembly phases	High: meetings during tendering, assembly and production to align the suppliers and to control the work	Medium/low: meetings and strong information exchange during the design phase. No more connection during the assembly	Medium/low: information sharing for the modules tolerance. Meetings during design phase	Medium/low: meeting during the tender. No more meetings between suppliers that deliver different modules	Medium/low: For critical modules, meetings and co-location. Off-the-shelf modules purchased on a catalogue
Suppliers involvement in design	High: for all the critical suppliers, systems suppliers, contractors	Medium: for all the suppliers but with different importance	Medium/low: only wood suppliers are involved. Finishing suppliers (systems and furniture) are involved later	High: strong conjoint design between the two wood manufacturers. Many reviews scheduled	High: all the suppliers are strongly involved, except the ones providing a real standard product
Customer involvement	High: customer reviews every single detail and influences mostly design and finishing	Low: some meetings in the early phases. No meetings afterwards	Medium: customer provide guidelines for the design and then follows the project on site	Medium: customer is involved in the design phase	Medium/high: customer is strongly involved in the design of the aesthetics, and supervise the finishing
Long term relationship with suppliers	Low: the SC is set up for the project only	None	None	None	Medium: for the hull and decks suppliers
Content of the transaction	Simple elements	Mainly subassemblies	Subassemblies and simple elements		Many items purchased as subassemblies, thus shifting the responsibility to the suppliers.
Geographical proximity	Relatively low: suppliers are located in Europe and spread in Italy	Relatively low: suppliers are regional but spread	High: suppliers are in Italy	High: suppliers in Italy, all in the same area apart from one Austrian supplier	Low: suppliers are all around Europe
Problems during the module pairing	Tolerances, suppliers not well coordinated, on-site reworks, errors	None	Too narrow interfaces (due to the weather conditions)	Rare	Too narrow interfaces
Avoiding problems during module pairing	Information sharing among SC partners, tight control, co-location with critical suppliers	If a problem occurs, it is faced during the design phase	"We've given up using dovetail connections, because with humidity the wood expands"	Millimeter tolerance in the plant craft	Clearly define all the interfaces, allow loosely coupled interfaces and provide specific design
Coping with problems during module pairing	Reworks	–	Rework	–	Gather on site all the suppliers that manage the modules during the assembly
Specific skills required	Project management for the coordination of more than 150 people	Design, crane usage, transportation optimization	Managing large 2D modules, and modules that embed some other systems (like the roof)	Managing large modules on the yard. Coordinating transportations from abroad	Coordinating many suppliers. Identifying features that can be postponed
Flexibility to changes in design	High: changes in the last phases happened and were quite easy to solve	Low: changes in the last phases were very rare and very dangerous	Medium: changes in the last phases were allowed but only provided they had reduced impact on lead time and costs	Medium: changes in the last phases were allowed but only provided they had reduced impact on lead time and costs	High: changes in the last phases were possible and frequent
Approaches followed to cope with changes in design	Carry out an ad hoc solution. Meet all of them if several suppliers are involved	Anticipate all the constraints during design, which leads to higher design costs	Structural module cannot be changed	Reworks	Postpone the design and the production of most customizable features
Lead time	Long: customers were highly satisfied by the quality of the results, but delay caused dissatisfaction	Short: customers were highly satisfied by price saving, schedule respect and short lead time	Short: customers were highly satisfied by schedule respect and short lead time	Short: customers were highly satisfied by short lead time	Medium: customers were highly satisfied by quality and schedule respect

References

Adebayo, A.K., Price, A.D.F., Gibb, A.G.F., 2006. Impact of modern methods of construction on healthcare infrastructure. ARCOM Conf., 969–977.
Agarwala, N. (2014). Developments in modular construction for shipbuilding. In: Proceedings of the International Seminar on Future Trends and Opportunities in Warship Design and Construction, New Delhi, September 25 , pp. 1–11.
Baldwin, C.Y., Clark, K.B., 1997. Managing in an age of modularity. Harvard Bus. Rev. 75 (5), 84–93.
Bankvall, L, Bygballe, L.E., Dubois, A., Jahre, M., 2010. Interdependence in supply chains and projects in construction. Supply Chain Manage.: Int. J. 15 (5), 385–393.
Barlow, J., Childerhouse, P., Gann, D., Naim, M., Ozaki, R., Road, E., Drive, C., 2003. Choice and delivery in house building: lessons from Japan for UK house builders. Build. Res. Inf. 31 (2), 134–145.
Barlow, J., Ozaki, R., 2005. Building mass customized housing through innovation in the production system: lessons from Japan. Environ. Plann. 37 (1), 9–20.
BEA (2014) ⟨http://www.bea.gov/industry/gdpbyind_data.htm⟩.
Benton, W.C., McHenry, L.F., 2010. Construction Purchasing and Supply Chain Management. McGraw Hill, New York, NY.
Björnfot, A. (2004). Modular Long-Span Timber Structures—A Systematic Framework for Buildable Construction. Thesis.
Bowersox, D.J., Daugherty, P.J., 1995. Logistics paradigms: the impact of information technology. J. Bus. Logist. 16 (1), 65–80.
Browning, T.R., 2001. Applying the design structure matrix to system decomposition and integration problems: a review and new directions. IEEE Trans. Eng. Manage. 48 (3), 292–306.
Brun, A., Pero, M., 2012. Measuring variety reduction along the Supply Chain: the Variety Gap Model. Int. J. Prod. Econ. 139 (2), 510–524.
Campagnolo, D., Camuffo, A., 2010. The concept of modularity in management studies: a literature review. Int. J. Manage. Rev. 12 (3), 259–283.
Caridi, M., Cigolini, R., De Marco, D., 2006. Linking autonomous agents to CPFR to improve SCM. J. Enterp. Inf. Manage. 19 (5), 465–482.
Caridi, M., Pero, M., Sianesi, A., 2012. Linking product modularity and innovativeness to supply chain management in the Italian furniture industry. Int. J. Prod. Econ. 136 (1), 207–217.
Castellano, A., Cigolini, R., 2002. Using modularization to manage construction projects of onshore process plants: a theoretical approach and a case study. Project Manage. J. 33 (2), 29–40.
CERF (1996). Construction Industry Research Prospectuses for the 21st Century. Report 96-5016.
Cigolini, R., Pero, M., Rossi, T., Sianesi, A., 2014. Linking supply chain configuration to supply chain performance: a discrete event simulation model. Simul. Modell. Pract. Theory 40, 1–11.
Cigolini, R., Pero, M., Rossi, T., Sianesi, A., 2013a. Using simulation to optimize transhipment systems: applications in field. Marit. Econ. Logist. 15 (3), 332–348.
Cigolini, R., Pero, M., Rossi, T., 2013b. Sizing offshore transhipment systems: a case study in maritime dry-bulk transportation. Prod. Plann. Control 24 (1), 15–27.
Cigolini, R., Pero, M., Rossi, T., 2011. An object-oriented simulation meta-model to analyze supply chain performance. Int. J. Prod. Res. 49 (19), 5917–5941.
Cigolini, R., Rossi, T., 2010. Managing operational risks along the oil supply chain. Prod. Plann. Control 21 (5), 452–467.
Cigolini, R., Rossi, T., 2008. Evaluating supply chain integration: a case study using fuzzy logic. Prod. Plann. Control 19 (3), 242–255.
Chryssolouris, G., Makris, S., Xanthakis, V., Mourtzis, D., 2004. Towards the Internet-based supply chain management for the ship repair industry. Int. J. Computer Integr. Manuf. 17 (1), 45–57.
Collins, R., Bechler, K., Pires, S., 1997. Outsourcing in the automotive industry: from just in time to modular consortia. Eur. Manag. J. 15 (5), 498–508.
De Blok, C., Meijboom, B., Luijkx, K., Schols, J., 2013. The human dimension of modular care provision: opportunities for personalization and customization. Int. J. Prod. Econ. 142 (1), 16–26.
Dekkers, R, Chang, C.M., Kreutzfeldt, J., 2013. The interface between "product design and engineering" and manufacturing: a review of the literature and empirical evidence. Int. J. Prod. Econ. 144 (1), 316–333.
Doran, D., Giannakis, M., 2011. An examination of a modular supply chain: a construction sector perspective. Supply Chain Manage.: Int. J. 16 (4), 260–270.
Doran, D., 2003. Supply chain implications of modularization. Int. J. Oper. Prod. Manage. 23 (3), 316–326.
Doran, D., 2004. Rethinking the supply chain: an automotive perspective. Supply Chain Manage.: Int. J. 9 (1), 102–109.
Droge, C., Jayaram, J., Vickery, S.K., 2004. The effects of internal versus external integration practices on time-based performance and overall firm performance. J. Oper. Manage. 22 (6), 557–573.
Droge, C., Vickery, S., Jacobs, M., 2012. Does supply chain integration mediate the relationships between product/process strategy and service performance? An empirical study International J. Prod. Econ. 137 (2), 250–262.
Duray, R., Ward, P.T., Milligan, G.W., Berry, W.L., 2000. Approaches to mass customization: configurations and empirical validation. J. Oper. Manage. 18 (6), 605–625.
Eisenhardt, K.M., 1989. Building theory from case study research. Acad. Manage. Rev. 14 (4), 532–550.
Eriksson, P.E., 2010. Improving construction supply chain collaboration and performance: a lean construction pilot project. Supply Chain Manage.: Int. J. 15 (5), 394–403.
Fine, C.H., 1998. Clockspeed: Winning Industry Control in the Age of Temporary Advantages.
Fisher, M., 1997. What is the right Supply Chain for your product? Harvard Business Review 75 (2), 105–116.
Frohlich, M.T., Westbrook, R., 2001. Arcs of integration: an international study of supply chain strategies. J. Oper. Manage. 19 (2), 185–200.
Gann, D., 1996. Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan. Constr. Manage. Econ. 14, 437–450.
Garver, S.N., Edyvane, J. (2010). Ship modularity cost-reduction models. In: Proceedings of the Automation and Controls Symposium of ASNE—American Society of Naval Engineers, Milwakee, WI, August, 10th–11th, pp. 1–12.
Gibb, A.G.F., Isack, F., 2003. Re-engineering through pre-assembly: client expectations and drivers. Build. Res. Inf. 31 (2), 146–160.
Gil, N., Tether, B.S., 2011. Project risk management and design flexibility: analysing a case and conditions of complementarity. Res. Policy 40 (3), 415–428.
Gockowski, K. (2005) "Modularization in ship equipment—opinion of modularization degree in existing naval constructions (Based on Polish and Northern Europe shipyard experiences)", Report within the Framework of Project "Intermodul" s/03/G IntermareC.
Gosling, J., Naim, M.M., 2009. Engineer-to-order supply chain management: a literature review and research agenda. Int. J. Prod. Econ. 122 (2), 741–754.
Gosling, J., Naim, M., Towill, D., 2012. A supply chain flexibility framework for engineer-to-order systems. Prod. Plann. Control 24 (7), 1–15.
Granderson, M., 2007. Unique hazards of shipbuilding and modular construction. Occup. Health Saf. 76 (8), 54–56.
Halse, L.L., 2014. Global value chains in shipbuilding: governance and knowledge exchange, In: Proceedings of IFIP WG 5.7 International Conference, APMS 2014, Ajaccio, France, September 20–24. Springer Berlin Heidelberg Publisher, pp. 209–216.
Handfield, R.B., Nichols, E.L., 1999. Introduction to Supply Chain Management. Prentice-Hall, Upper Saddle River, NJ.
Hofman, E., Voordijk, H., Halman, J., 2009. Matching supply networks to a modular product architecture in the house-building industry. Build. Res. Inf. 37 (1), 31–42.
Hunt, T.E. (2014). NSWCCD Ship Design Group Hosts Modular Ship Design Pioneer, Waves, December, pp. 25.
Jaillon, L., Poon, C.S., 2008. Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study. Constr. Manage. Econ. 26 (9), 953–966.
Jiang, L., Bastiansen, E., Strandenes, S.P., 2013. The international competitiveness of China's shipbuilding industry. Transp. Res. Part E 60, 39–48.
Jones, E., Bolander, W., Fu, F.Q., 2008. Product innovativeness, customer newness, and new product performance: a time-lagged examination of the impact of salesperson selling intentions on new product performance. J. Pers. Sell. Sales Manage. 28 (4), 351–364.
Kolić, D., Fafandjel, N., Bićanić, D., 2010. Proposal for the determination of technological parameters for design rationalization of a shipbuilding produc-tion program. Eng. Rev. 30 (2), 59–69.
Lamberti, L., Pero, M., 2013. The supply chain management–marketing interface in product development: an exploratory study. Bus. Process Manage. J. 19 (2), 217–244.
Lau, A.K.W., Yam, R.C.M., Tang, E., 2007. The impacts of product modularity on competitive capabilities and performance: an empirical study. Int. J. Prod. Econ. 105 (1), 1–20.
Lau, A.K.W., Yam, R.C.M., Tang, E., 2011. The Impact of Product Modularity on New Product Performance: Mediation by Product Innovativeness. J. Product Innov. Manag. 28, 270–284.
Lee, D., Park, J., Pulshashi, I.R., Bae, H., 2013. Clustering and operational analysis for assembly blocks using process mining in shipbuilding industry, In: Proceedings of the First Asia Pacific Conference, AP-BPM, Beijing, China, August 29–30, 2013. Springer International Publishing, Switzerland, pp. 67–80.
Lönngren, H.M., Rosenkranz, C., Kolbe, H., 2010. Aggregated construction supply chains: success factors in implementation of strategic partnerships. Supply Chain Manage.: Int. J. 15 (5), 404–411.
Miles, M., Huberman, A.M., 1984. Qualitative Data Analysis. Sage Publications, Beverly Hills, CA.
Mohamad, A., Hickethier, G., Hovestadt, V., Gehbauer, F. (2013). Use of modularization in design as a strategy to reduce component variety in one-off projects, In: Proceedings of the IGLC-21 Conference, Fortaleza, Brazil, July, pp. 289–298.
Naim, M., Barlow, J., 2003. An innovative supply chain strategy for customized housing. Constr. Manage. Econ. 21 (6), 593–602.
O'Brien, W., Formoso, C.T., Vrijoef, R., London, K.A., 2009. Construction Supply Chain Management Handbook. CRC Press—Taylor & Francis Group, Boca Raton, FL.
Ortiz, O., Castells, F., Sonnemann, G., 2009. Sustainability in the construction industry: a review of recent developments based on LCA. Constr. Build. Mater. 23, 28–39.
Pan, W., Gibb, A.G.F., Dainty, A.R.J., 2008. Leading UK house builders' utilization of offsite construction methods. Build. Res. Inf. 36 (1), 56–67.
Park, K., Lee, K., Park, S., Kim, S., 1996. Modeling and solving the spatial block scheduling problem in a shipbuilding company. Comput. ind. eng. 30 (3), 357–364.

Pero, M., Abdelkafi, N., Sianesi, A., Blecker, T., 2010. A framework for the alignment of new product development and supply chains. Supply Chain Manage.: Int. J. 15 (2), 115–128.
Petersen, K., Handfield, R., Ragatz, G., 2005. Supplier integration into new product development coordinating product, process and supply chain design. J. Oper. Manage. 23, 371–388.
Pine, J. (1999). Mass Customization: The New Frontier in Business Competition.
Pryke, S.D., 2004. Analysing construction project coalitions: exploring the application of social network analysis. Constr. Manage. Econ. 22 (8), 787–797.
Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., Zimmerman, J.B., 2012. Construction matters: comparing environmental impacts of building modular and conventional homes in the United States. J. Ind. Ecol. 16 (2), 243–253.
Reis, J.G.M., Machado, S.T., Neto, P.L.O.C., Naas, I.A., 2014. Aligning supply chain strategies with product life cycle stages, In: Proceedings of IFIP WG 5.7 International Conference, APMS 2014, Ajaccio, France, September 20–24. Springer Berlin Heidelberg Publisher, pp. 3–10.
Ro, Y.K., Liker, J.K., Fixson, S.K., 2007. Modularity as a strategy for supply chain coordination: the case of U.S. auto. IEEE Trans. Eng. Manage. 54 (1), 172–189.
Rubeša, R., Fafandjel, N., Kolić, D., 2011. Procedure for estimating the effectiveness of ship modular outfitting. Eng. Rev. 31 (1), 55–62.
Sambasivan, M., Soon, Y.W., 2007. Causes and effects of delays in Malaysian construction industry. Int. J. Project Manage. 25 (5), 517–526.
Sanchez, R., Mahoney, J., 1996. Modularity, flexibility and knowledge management in product and organization design Special Issue: Knowledge and the Firm. Strateg. Manage. J. 17, 63–76.
Schoenwitz, M., Naim, M., Potter, A., 2012. The nature of choice in mass customized house building. Constr. Manage. Econ. 30 (3), 203–219.
Segerstedt, A., Olofsson, T., 2010. Supply chains in the construction industry. Supply Chain Manage.: Int. J. 55 (5), 347–353.
Seubert, T.W., 1988. Modular Shipbuilding and its Relevance to Construction of Nuclear Power Plants M.S. Thesis in Nuclear Engineering. Massachusetts Institute of Technology, May.
Ulku, S., Schmidt, G.M., 2011. Matching product architecture and supply chain configuration. Prod. Oper. Manage. 20 (1), 16–31.
Ulrich, K., 1995. The role of product architecture in the manufacturing firm. Res. Policy 24 (3), 419–440.
Voordijk, H., Meijboom, B., Haan, J. De, 2006. Modularity in supply chains: a multiple case study in the construction industry. Int. J. Oper. Prod. Manage. 26 (6), 600–618.
Voss, C., Tsikriktsis, N., Frohlich, M., 2002. Case research in operations management. Int. J. Oper. Prod. Manage. 22 (2), 195–219.
Vrijhoef, R., Koskela, L., 2000. The four roles of supply chain management in construction. Eur. J. Purch. Supply Manage. 6 (3-4), 169–178.
Yin, R.K., 1984. Case study Research: Design and Methods. SAGE Publication, CA.