The Impact of Industry 4.0 on Supply Chain Coordination in Engineer-To-Order Companies

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Abstract: Companies operating with an Engineer-to-Order (ETO) fulfilment strategy deliver highly customized products, which makes downstream supply chain coordination critical for their success. Recent studies have shown that Industry 4.0 technologies can facilitate supply chain coordination. However, it is still unclear how they could support downstream coordination in ETO companies. The purpose of this paper is to start to fill in such gap. To do so, we conducted a multiple case study research, encompassing 12 ETO Italian companies from the machinery, shipbuilding, and aerospace industries. By integrating the results of the case studies with the extant literature on supply chain coordination, we classify downstream coordination mechanisms in ETO contexts according to three axes: the typology (standards, schedules and plans, mutual adjustments, and teams), the product life-cycle phase (pre-project, design, manufacturing, and after-sales), and the type of technology adopted (if any). Then, we focus on the coordination mechanisms enabled by Industry 4.0, discussing the critical success factors for their implementation and their impact on supply chain performance. Therefore, from a theoretical perspective, this research builds upon and expands the literature on supply chain coordination mechanisms in ETO contexts by enriching the frameworks from the literature with the after-sales phase as well as discussing how Industry 4.0 technologies can support downstream supply chain coordination. Moreover, insights on the differences among sectors are presented. From a practical perspective, our results may guide managers of ETO companies in the choice of the downstream coordination mechanisms, according to their expected benefits and challenges, as well as in understanding how Industry 4.0 can support them in coordinating with their customers.

Keywords: Engineer-to-Order; ETO; Industry 4.0; Supply Chain; Coordination

I. Introduction

Engineer-to-Order (ETO) supply chains involve multiple companies performing a wide range of activities (Hicks *et al.*, 2000). To align the interests of the different actors of the ETO supply chains, Supply Chain Coordination (SCC) mechanisms are needed (Sahin and Robinson, 2002). SCC mechanisms have been discussed by past studies, especially by Adler (1995) and Twigg (2002).

Among the others, companies operating in the ETO supply chains need to align with their customers. This type of SCC is called Downstream Supply Chain Coordination (DSCC). DSCC is fundamental in ETO supply chains, given that products delivered by ETO supply chain are highly customized (Cannas et al. 2019)

However, literature is scarce in discussing DSCC and empirical studies are mostly focused on shipbuilding (Mello et al. 2015a, 2015b, 2017). This is a gap that deserves further investigation because DSCC may significantly impact on ETO projects, especially in the sourcing and execution stages (Dixit *et al.*, 2019).

Furthermore, few papers discuss the impact of technologies on DSCC in ETO supply chains, especially when it comes to the most recent technologies, emerged during the Fourth Industrial Revolution, also known as Industry 4.0 (I4.0). This gap deserves further attention since the impact of I4.0 on the supply chain performance of an ETO firm might be huge, as recent studies have suggested. For instance, the simulation study by Chen *et al.* (2020) shows that using I4.0 technologies could potentially reduce the time to deal with design changes up to 18%.

Therefore, the purpose of this paper is to fill in these two gaps, by addressing the following research questions (RQs):

RQ1. Which mechanisms do ETO companies adopt to achieve DSCC?

RQ2. What are the drivers and barriers to the adoption of I4.0 technologies to support DSCC in ETO supply chains?

RQ3. How do I4.0 technologies impact on ETO companies performance?

To answer these RQs, we adopted a multiple case study methodology (described in Section III), encompassing 12 ETO Italian companies belonging to the machinery, shipbuilding, and aerospace industries. After analysing the results of our case studies, we developed a taxonomy of DSCC mechanisms in ETO contexts (Section IV.A), and we discussed the benefits and challenges of the different I4.0 technologies observed

(Section IV.B). Then, we discussed more deeply such results (Section V), by comparing them with the literature previously reviewed (Section II). Finally, we presented the answers to our RQs, our contributions to theory and to practice, and some future research directions (Section VI).

II. Theoretical Background

The phrase "Engineer-to-Order" (ETO) indicates an order fulfilment strategy characterized by the Customer Order Decoupling Point (CODP) – the point in a process which separates forecast-driven activities from order-driven ones – located at the engineering phase (Gosling and Naim, 2009). In fact, ETO companies perform all the activities from engineering onwards based on specific customer orders. In fact, typical ETO companies operate in industries characterized by high levels of product customization, such as construction, shipbuilding, Oil & Gas (O&G), aerospace, and machinery (Cannas and Gosling, 2021). All these contexts are typically featured by extreme levels of product complexity, to deal with which a proper SCC is fundamental (Shurrab *et al.*, 2020).

In general, SCC consists in the managerial activities put in place by companies for aligning the decisions of different parties with the final objective to achieve a common goal (Sahin and Robinson, 2002). To support SCC, companies may adopt several coordination mechanisms. Adler (1995) classified them in four categories – "standards", "schedules and plans", "mutual adjustment", and "teams" – which can be adopted across three stages of a Project's Life Cycle (PLC): pre-project, engineering, and production. Adler's framework focuses on the coordination mechanisms used integrate the design and the manufacturing processes: as such, it is limited to an "intra-company" perspective. For this reason, some years later, Twigg (2002) extended Adler's work to address inter-company issues, especially upstream (i.e., with suppliers) SCC.

The frameworks by Adler and Twigg served as a basis for the work by Mello *et al.* (2015b), who performed an in-depth case study that identified twelve coordination mechanisms adopted during a shipbuilding PLC, pointing out how the most interactive coordination mechanisms (e.g., joint development) could decrease delays by allowing higher concurrency, although at the price of higher coordination costs. In addition, Mello *et al.* (2015a) identified, by means of a multiple case-study, seven factors affecting SCC in shipbuilding contexts, among which the integration between engineering and production and the production capability turned out to be the most relevant variables. Remarkably, none of these two papers discussed the impact of technology on SCC, which could have suggested a low importance of this aspect. However, in the more recent work by Mello *et al.* (2017), in which they outlined seven principles to improve SCC in a shipbuilding ETO supply chain, they pointed out the need to extend the use of IT systems, which had been traditionally quite limited in the shipbuilding sector. In fact, other studies conducted in the construction industry showed how digital technologies can have a dramatic impact on SCC, especially when it comes to I4.0.

I4.0 is a concept introduced at the 2011 Hannover Fair in Germany (Ghobakhloo, 2018) to refer to the Industrial Revolution characterized by the integration between manufacturing operations systems and Information and Communication Technologies (ICT) – an integration which gives birth to the so-called Cyber-physical Production Systems (CPS), which are the "core" of I4.0 (Dalenogare *et al.*, 2018).

I4.0 has been conceptualized in many different ways in the last decade. In particular, we based our study on the framework proposed by Boston Consulting Group (BCG) in 2015, due to its wide recognition by both practitioners and academics (e.g., Rüßmann *et al.*, 2015; Vaidya *et al.*, 2018; Hernandez-de-Menendez *et al.*, 2020; Machado *et al.*, 2020). According to such framework, I4.0 is based on nine "pillars": Big Data Analytics (BDA); autonomous robots; simulations; horizontal and vertical system integration; Industrial Internet of Things (IIoT); cybersecurity; cloud computing and data storage; additive manufacturing; and augmented reality (Rüßmann *et al.*, 2015). Remarkably, all these pillars – except for horizontal and vertical systems integration – depend on technologies different from those used during the Third Industrial Revolution, which we will refer to as "I3.0" technologies. Examples of I3.0 technologies include web-based and desktop applications, product configurators, Service Oriented Architectures (SOA), Discrete Event Simulations (DES), Manufacturing Execution Systems (MES), Computer-Aided Design (CAD), or Computer-Aided Manufacturing (CAM) (Tu *et al.*, 2006; Özbayrak *et al.* 2007; Chan *et al.*, 2009; Cannas *et al.*, 2020). For the sake of simplicity, we will classify as "I3.0" all those technologies that do not belong to any of the nine pillars present in the BCG framework.

I4.0 impacts on every aspect of modern organizations. In particular, to measure the impact of I4.0 on supply chain performance, Fredrico *et al.* (2021) developed a Supply Chain 4.0 Scorecard, based on the balanced scorecard by Kaplan and Norton (1996). It consists of four areas, each one with its measurement approaches: "financial results" (e.g., profitability), "customers" (e.g., level of customer interaction on processes), "business processes" (e.g., level of collaboration), and "learning and growth" (e.g., coordination effectiveness). Because of its fit with our RQs, we chose this framework to help us assess how I4.0 impacts on DSSC in ETO firms.

When it comes to the adoption of I4.0 to support SCC in ETO contexts, the main academic contributions refer to the construction sector. The systematic literature review by Dallasega *et al.* (2018) pointed out that I4.0 technologies can favour synchronization between the suppliers and the construction site, thus increasing technological, organizational, geographical and cognitive proximity. This result has been validated by a more recent case-based simulation study, which showed how the real-time information exchanges enabled by I4.0 technologies could dramatically reduce buffer sizes and construction lead times (Dallasega *et al.*, 2019). Such positive impact of I4.0 on the management of material flows in construction sites has been confirmed by the previously mentioned work by Chen *et al.* (2020), and discussed by Patrucco *et al.* (2020) too. Interestingly, though, none of the aforementioned papers discusses the impact of I4.0 on DSSC, which contrasts with the high importance attributed to joint development and other DSSC mechanisms pointed out by Mello *et al.* (2015a, 2015b, 2017).

In conclusion, we observed a need to extend the research on SCC in ETO contexts with a study focused only on DSSC, but with a more cross-sectorial approach, and with an emphasis on technologies, especially I4.0 ones, whose actual benefits and challenges remain unclear with respect to DSSC.

III. METHODOLOGY

Given the broad nature of the RQs of this study, we believed the most suitable research methodology could be the case study one (Yin, 2018). More specifically, we conducted a cross-sectorial, multiple case study research, since it is considered able to provide more generalizable results by enabling a comparative analysis of the findings (Eisenhardt, 1989).

Initially, we selected a first set of potentially relevant companies by querying the database AIDA (https://aida.bvdinfo.com/), using the ATECO codes (ISTAT, 2022) to identify the ETO sectors of our interest. Then, we contacted a sample of 200 companies (100 machinery firms, 40 shipbuilding ones, 40 aerospace ones, and 20 O&G ones) by approaching them through their official emails, providing a cover letter and an abridged interview protocol. Eventually, we managed to interview 12 companies (10 from the machinery industry, 1 shipbuilding firm, and 1 aerospace one) through direct, semi-structured interviews. The interviews were performed via Microsoft Teams calls, in the period from June to August 2021.

For these interviews, we followed a semi-structured protocol, consisting in five sections: personal background of the interviewee (i.e. role, responsibility and seniority within the company); company overview (types of products and related engineering and production activities); coordination with customers (coordination mechanisms used, actors and organizational functions involved, and differences between the PLC stages); and role of I4.0 (technologies used, benefits and challenges assessed according to the frameworks reviewed in the literature). We conducted one interview with all the case companies of the sample, except for one of them (C8), which agreed to participate to a second round. On average, the interviews lasted 60 minutes, and were recorded (upon permission of the interviewees), so that they could then be transcribed, to better analyze the data gathered. Since the interviews were conducted entirely in Italian, we paid attention while translating their excerpts in English, to maintain the validity of our findings. Moreover, to ensure data triangulation (Voss *et al.*, 2002), we used both archival data (e.g., videos, documents, information from the companies' websites, and documentation provided by the interviewees) and financial information retrieved from the database AIDA. Moreover, interviewees played a wide range of roles, from sales managers to CEOs. The unit of analysis is the company and its coordination with customers. After transcribing the interviews, we analyzed them with an open coding approach, adopting a mix of in vivo and constructed codes (Glaser and Strauss, 1967). Then, we analyzed the data using within-case and cross-case methods (Eisenhardt and Graebner, 2007).

IV. RESULTS

Table I provides an overview of the key characteristics of the case companies. Both the companies' names and any other sensitive information have been anonymized for confidentiality reasons.

TABLE I
OVERVIEW OF THE 12 INTERVIEWED COMPANIES

Company	Approximate Turnover* (2020) [M€]	Approximate Number of Employees* (2020)	Sector	Business Description
C1	10-50	50-250	M	Industrial chemical equipment
C2	>50	>250	M	Printing machinery
C3	2-10	10-50	M	Metal forming machinery
C4	2-10	10-50	A	Aerospace parts
C5	10-50	10-50	S	Luxury shipyards
C6	10-50	10-50	M	Textile machinery
C7	10-50	50-250	M	Printing machinery
C8	>50	>250	M	Packaging machinery
C9	10-50	50-250	M	Air purification equipment
C10	2-10	10-50	M	Plastic forming machinery
C11	2-10	10-50	M	Plastic forming machinery
C12	10-150	50-250	M	Industrial robots

*Ranges based on European Recommendation 2003/361/EC
Legend: M = Machinery; A = Aerospace; S = Shipbuilding

A. ETO Downstream Coordination Mechanisms

From the interviews performed, 20 DSSC mechanisms emerged, which were arranged in Table II. The table is divided in 4 sections, one for each phase of the PLC discussed in the cases. Remarkably, on top of the three PLC stages already discussed by Adler (1995) and Mello *et al.* (2015b), we also considered the After-Sales phase, since our interviews showed its high relevance for today's ETO companies. For space constraints, we stacked each section one below the other. Then, for each PLC stage, we classified the coordination mechanisms observed in the cases within each of the four coordination approaches of Adler's framework: standards, schedules and plans, mutual adjustment, and teams. We also listed, for each coordination mechanism, the companies in which it was observed.

TABLE II
COORDINATION MECHANISMS ALONG THE PLC

Pre-Project Phase	
Standards	CAD/CAM software: C1; C2; C3; C4; C5; C6; C7; C9; C10; C11; C12
	Simulation software: C2; C3; C4; C5; C6; C7: C8; C12
	Cloud platforms: C4; C7
	Stage gate process: C1; C4; C5; C6
Schedules and Plans	Big Data Analytics: C1; C2; C3; C4; C6; C7; C8; C9; C10; C12
	Project management software: C1; C5; C9; C12
Mutual Adjustment	Augmented Reality enabled-design: C5; C8
	Coordinating role (Project Manager): C1; C2; C3; C4; C7; C8; C9
	Coordinating role (Product Manager): C2; C4; C8; C9; C10; C11
	Kick-off meetings: C3; C4; C5; C6; C9; C10; C12
Teams	Joint development: C4
Design Phase	
Standards	CAD/CAM software: C1; C2; C4; C5; C6; C7; C9; C10; C11; C12
	Simulation software: C2; C3; C4; C5; C6; C7; C8; C12
	Cloud platforms: C4; C7
	Cybersecurity for protected data exchange: C4
	Stage gate process: C1; C4; C5; C6
	Product configurators: C6
Schedules and Plans	Big Data Analytics: C1; C2; C3; C4; C6; C7; C8; C9; C10; C12
	Project management software: C1; C5; C9; C12
	Technical tests: C2; C5; C4; C7; C8; C9; C11; C12
	ERP management systems: C1; C4; C6; C7; C9
Mutual Adjustment	Augmented Reality enabled-design: C5; C8
	Coordinating role (Project Manager): C1; C2; C3; C4; C7; C8; C9
	Design reviews: C3; C4; C5; C6; C8; C9; C10
Teams	Joint development: C4
Manufacturing Phase	
Standards	Cloud platforms: C4
	Cybersecurity for protected data exchange: C4
Schedules and Plans	Big Data Analytics: C1; C2; C3; C4; C6; C7; C8; C9; C10; C12
	Project management software: C1; C5; C9; C11
	ERP management systems: C1; C4; C6; C7; C9
Mutual Adjustment	Coordinating role (Project Manager): C1; C2; C3; C4; C7; C8; C9
	Manufacturing reviews: C7; C8
Teams	
After-Sales Phase	
Standards	Simulation software: C2; C3; C4; C5; C6; C7; C8; C12
	Cloud platforms: C8; C11; C12
	Cybersecurity for protected data exchange: C4; C12
Schedules and Plans	Big Data Analytics: C1; C2; C3; C4; C6; C7; C8; C9; C10; C12
Mutual Adjustment	Coordinating role (Product Manager): C2; C4
	IIoT enabled-Remote Assistance: C2; C3; C4; C7; C8; C9; C10; C11
	Augmented Reality Remote Maintenance: C2; C6; C7; C8; C9; C11; C12
	Service Manager: C9
Teams	

By looking at each cell of the table, it is clear that companies are relying on both organizational (9 mechanisms) and technological (11) DSCC mechanisms. For the technological mechanisms, two types are observed: I3.0 and I4.0.

Organizational Coordination Mechanisms. As expected, most of these mechanisms are based on mutual adjustment. For instance, C9 employs a *Coordinating Role (Project Manager)* for inter-organizational communication and coordination through one-off meeting with customers, while C10 adopts a *Coordinating Role (Product Manager)* for either after-sales or pre-project communication with respectively historical or newly acquired customers. Moreover, *Kick-off Meetings* are adopted by most of the companies to analyse customers' product requirements, order details and plan future activities; finally, *Design Reviews*, implemented by C3, allow to periodically monitor the progress of a project according to customers' requirements, while *Manufacturing Reviews*, adopted by C7, help check and validate the production status. Other organizational mechanisms are: *Stage and Gate Processes*, which consist in sets of manufacturing milestones that must be approved by customers to proceed with orders; *Technical Tests*, adopted by C2, which allow to test in advance the product technical performance to meet customers' requirements; and *Joint Development*, consisting in ad-hoc teams created with the customers, as implemented by C4, to co-design and develop together products' characteristics.

I3.0 Coordination Mechanisms. Besides the already mentioned *CAD/CAM Software*, other I3.0 technologies observed are *Project Management Software* – used by C5 to support project managers in communicating project status or plans with customers, as well as monitoring the overall order lead time and costs – and *ERP Management Systems,* which help C6 achieve organizational coordination with customers through real-time information and data exchanges.

I4.0 Coordination Mechanisms. Interestingly, I4.0 supports all the coordination approaches, except for teams. For what concerns standards, most companies adopt *Simulation software,* which allows to create "virtual prototypes" of products, by enabling real-time design modifications according to customers' requests. Instead, *Cloud-based platforms* support coordination with customers by enabling the exchange of files/data/drawings for specifications along all the phases of the PLC. Moreover, the aerospace company C4 adopts *Cybersecurity for protected data exchange* designed to protect networks and data, allowing a safer and secure coordination and information interchange. Moving to schedules and plans, C12 represents an interesting case, since it exploits *Big Data Support & Analytics* for both data collection and system interconnection, enabling all the different actors involved in the coordination activities to make decisions more accurately and quickly, using real-time data. This helps creating *Horizontal and Vertically integrated systems*, i.e. interconnected networks of cyber-physical and enterprise systems (horizontally) as well as all the different companies' functions (vertically), which allow a more effective and efficient level of coordination between ETO companies and customers. For what concerns mutual adjustment, it is interesting how C11 implemented *IIoT enabled-Remote Assistance*, to provide remote assistance to the customers in the after-sales phase, thanks to the interconnection between machines and systems through the Internet. Instead, C8 is the advocate of *Augmented Reality Remote Maintenance*: an after-sales coordination with customers through Augmented Reality solutions (e.g., AR glasses, tablet, cameras, smartwatch) to coordinate maintenance activities and support customers' operators. Finally, *Augmented Reality enabled design* supported by visors allows the customers, designers, and engineers of ETO companies to virtually envision how the finished product will look like, in order to provide the most suitable solution according to customers' requirements.

B. Barriers and drives to I4.0

Regarding I4.0 challenges, ETO companies are experiencing resistance from *Management* to these technologies, mainly because of a lack of *knowledge* about I4.0 technologies and their potentialities. Remarkably, this limitation is also widespread across the *less mature customers* who are both sceptic about the benefits of I4.0 and, often, unaware of the requirements in terms of *Legislation*. As C3 said, "*everyone likes having technology on the machine, but they don't realize that if they don't connect it to the internet it won't work, and they don't have the culture or the intention to take that extra step to make their investment something really effective*". Another major concern broadly diffused both across customers and ETO companies, is represented by *Data Privacy & Security*, which constitutes nowadays one of the major barriers slowing down the adoption of such technologies due to the great level of information sharing and integration enabled by I4.0. As C1 said, "*some [I4.0] suppliers also work with competitors… and the world of those who do our work is small… So, if we give confidential data to the supplier, there is a sharing of objectives, information and tools which we designed*".

In the face of these barriers, ETO companies are leveraging on drivers to overcome them. For instance, ETO companies are now introducing *new professional roles*, which are more technological oriented and better skilled to deal with I4.0 technologies. *New Business Units*, specifically related to the development of I4.0 projects, are established within some ETO companies, such as C2, who "*even opened a software house, to be able to make the machines more and more I4.0, and to be quick in responding to customer needs*". In fact, to cope with the internal lack of knowledge about I4.0, firms are looking for more expert partners, either in forms of *company acquisitions*, or as *suppliers*, provided they can adequately consult and follow them in the digitalization journey. Proper *communication programs* are also needed to spread the knowledge about the benefits deriving from I4.0, increasing employees' acceptance degree. To summarize, we can use the words of C1: "*this is a team effort, so you have to get as many people on board as possible. If you do it with a top-down approach, you might bring the hierarchies on board, people may be not convinced, and you need great conviction in the employees*".

C. Impact of Industry 4.0 on ETO DSCC

The results show positive impacts of I4.0 on ETO DSCC. These results can be measured against, the four dimensions of the Supply Chain 4.0 Scorecard. Indeed, from a *Financial* and *Business Process* perspective, interviewees mentioned both a reduction of costs for coordination activities and improvements in terms of lead times. Additionally, I4.0 enables a greater involvement of *Customers* in the processes, increasing their value-added perception and their satisfaction. From a *Learning & Growth* perspective, instead, such technologies show their greatest benefits thanks to the higher level of horizontal and vertical integration they disclose. Finally, an interesting multi-dimensional finding is the "*Servitization*" enabled by the great data availability provided by I4.0 technologies. In fact, servitization allows both ETO companies to enlarge their value proposition with the offering of additional services (i.e., remote technical assistance, predictive maintenance, etc.) impacting Financial and Customer dimensions of the scorecard, and at the same time increasing the level of collaboration and integration with customers, positively affecting both Business Process and Learning & Growth perspectives.

V. Discussion

Comparing our results with what was already present in the literature reviewed, we may identify two main areas of discussion: DSCC mechanisms, and sectorial aspects.

A. DSCC mechanisms

Our research confirms the validity of the framework developed by Adler (1995) and Twigg (2002). In fact, while the former was focused on inter-departmental internal coordination, and the latter on upstream SCC, we have shown how the coordination approaches identified by them hold true also when it comes to DSSC, and can be used to frame a wide range of coordination mechanisms.

However, we showed that it may be necessary to expand Adler (1995) and Twigg (2002)'s framework by including a fourth PLC stage – the after-sales one – since, according to most interviewees, this is critical for an effective, and long-lasting, DSCC.

Moreover, we detailed the technological mechanisms, by making a difference between I3.0 technologies and I4.0. In fact, from what we observed from our case studies in ETO contexts, the I4.0 can provide a wider tools for supporting DSCC than I3.0, although it comes with lots of barriers that still need to be overcome.

In line with previous research in ETO sectors (Patrucco *et al.*, 2020), our results suggest that I4.0 technologies can positively support supply chain management – in this case, DSCC – and allow companies to reduce costs and lead times. However, the organizational mechanisms that emerged from our sample are the same as those present before the introduction of I4.0 technologies, differently from what observed by Patrucco *et al.* (2020), who pointed out the birth of novel organizational mechanisms, too. This might be due to the level of adoption of I4.0 technologies in the different cases. In fact, the companies we analysed show different levels of adoption of I4.0 to support DSCC, from cases that are still stuck at I3.0 (e.g., C5), to others that have already adopted several I4.0 technologies (e.g., C8).

Moreover, in line with Calabrese *et al.* (2020), we noticed how most of our cases can be considered in the "Evolution" phase, in the sense that I4.0 is improving these companies' operational performance, but it is not changing their value proposition. Consequently, they may not be exploiting the full potential of I4.0, seeing I4.0 as mere a tool that can be used to make DSCC faster. In other words, these companies may be using I4.0 technologies as "fast I3.0" ones.

One reason for this may be related to the still limited range of technologies that these companies are using. In fact, literature is suggesting that I4.0 technologies are synergistic, in the sense that if they are used together than the benefits are higher. For instance, Porter (2014) pointed out how it is necessary to build and support a brand new technological infrastructure, consisting of multiple layers (hardware, software, cloud, security, and connectivity) to properly create smart, connected, products, which are at the core of I4.0, Clearly, most of our companies, have not achieved this synergistic effect, yet.

B. Sectorial Aspects

We expanded the literature on DSCC in ETO contexts, by adopting a cross-sectorial approach, albeit with a relevant focus on machinery industries (which, however, were the least discussed sector with respect to this subject). This allowed us to point out some differences across the three ETO industries we analysed.

Concerning the shipbuilding sector, the high reliance of C5 on non-technological coordination mechanisms may show a need for luxury customers to "touch" products, instead of relying on, for examples, simulations. Such low reliance of this shipbuilding company on technology confirms some insights from Mello *et al.* (2015a, 2015b), who pointed out how this sector is still lagging behind in terms of digitalization.

Machinery companies were those richest of insights when it came to after-sales DSSC and, particularly, servitization. According to certain cases, such as C7 and C8, this may represent an opportunity to enrich these companies' business models: "*the business models with certain customers and the services offered are also changing; for instance, training was not provided until a few years ago"* (C7).

Conversely, the aerospace company C4 was one of the most concerned with data security, an aspect which deserved little attention by other cases, and which may deserve further investigation.

VI. CONCLUSIONS

This paper investigates the use of I4.0 technologies to support DSCC along the ETO supply chains, by means of twelve case studies across Italian machinery, shipbuilding and aerospace industries.

Results show I4.0 is used to support ETO companies along the pre-project, product design and manufacturing phases in sharing real-time data and allowing fast modifications to designs. In these phases, I4.0 is used in addition to the existing I3.0 technological solutions to supports the traditional organizational mechanisms, e.g. project mangers or design review. In the after sales, instead, I4.0 enabled companies to offer remote maintenance processes, thus not only smoothing the DSCC in that phase, but also changing the value proposition of companies. Moreover, the analysed cases highlighted that the main problem encountered by companies in implementing I4.0 is connected to the lack of maturity, in terms of knowledge, of the actors along the supply chain. Therefore, companies are looking for competences and knowledge outside their boundaries.

This paper contributes to the debate on the implications of I4.0 in ETO supply chains, by providing empirical evidence of the use of I4.0 to support DSCC. From a managerial perspective, the paper provides managers indications of which technology can be used to support the various development and after-sales phases. Moreover, it suggests companies should invest in developing new competences and knowledge to fully exploit the potential of the new technologies.

This paper is a first explorative attempt to investigate the use of I4.0 in ETO companies to support DSCC. The results are based on a limited sample of companies and the benefits are measured qualitatively. Further research is needed to further investigate, e.g. by using quantitative approaches, the results obtained, as well to see whether the type of DSCC mechanism may vary depending on some project features. Moreover, other ETO sectors neglected by this study, such as construction, may be further investigated.

REFERENCES

[1] Adler, P.S. (1995). Interdepartmental interdependence and coordination: The case of the design/manufacturing interface. *Organization Science*, 6(2), pp. 147-167.

[2] Alfnes, E., Gosling, J., Naim, M. and Dreyer, H.C. (2021). Exploring systemic factors creating uncertainty in complex engineer-to-order supply chains: Case studies from Norwegian shipbuilding first tier suppliers. *International Journal of Production Economics*, 240, pp. 108211.

[3] Bureau Van Dijk (2020). Analisi Informatizzata delle Aziende Italiane (AIDA). Available at: https://aida.bvdinfo.com/version-202241/home.serv?product=AidaNeo (Accessed: 15 April 2021)

[4] Cannas, V.G., Gosling, J., Pero, M. and Rossi, T. (2019). Engineering and production decoupling configurations: an empirical study in the machinery industry. *International Journal of Production Economics*, 216, pp. 173-189.

[5] Cannas, V.G., Masi, A., Pero, M. and Brunø, T.D. (2020). Implementing configurators to enable mass customization in the Engineer-to-Order industry: a multiple case study research. *Production Planning & Control*, pp. 1-21.

[6] Chan, H.K. and Chan, F.T. (2009). Effect of information sharing in supply chains with flexibility. *International Journal of Production Research*, 47(1), pp. 213-232.

[7] Dallasega, P., Rojas, R.A., Bruno, G. and Rauch, E. (2019). An agile scheduling and control approach in ETO construction supply chains. *Computers in Industry*, 112, pp. 103122.

[8] Dallasega, P., Rauch, E. and Linder, C. (2018). Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry*, 99, pp. 205-225.

[9] Dixit, V., Chaudhuri, A. and Srivastava, R.K. (2019). Assessing value of customer involvement in engineered-to-order shipbuilding projects using fuzzy set and rough set theories. *International Journal of Production Research*, 57(22), pp. 6943-6962.

[10] Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review*, *14*(4), pp. 532-550.

[11] Eisenhardt, K. M., & Graebner, M. E. (2007). Theory building from cases: Opportunities and challenges. *Academy of Management Journal, 50*(1), pp. 25-32.

[12] European Commission (2003). EU Recommendation 2003/361 concerning the definition of micro, small and medium-sized enterprises. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32003H0361 (Accessed: 15 April 2022)

[13] Frederico, G.F., Garza-Reyes, J.A., Kumar, A. and Kumar, V., (2020). Performance measurement for supply chains in the Industry 4.0 era: a balanced scorecard approach. *International Journal of Productivity and Performance Management.*

[14] Glaser, B. G. & Strauss, A. L. (1967). *The Discovery of Grounded Theory. Strategies for Qualitative Research*. Aldine, Chicago.

[15] Ghobakhloo, M. (2018). The future of manufacturing industry: a strategic roadmap toward Industry 4.0. *Journal of Manufacturing Technology Management*.

[16] Gosling, J. and Naim, M.M. (2009). Engineer-to-order supply chain management: A literature review and research agenda. *International Journal of Production Economics*, 122(2), pp. 741-754.

[17] Hernandez-de-Menendez, M., Morales-Menendez, R., Escobar, C.A. and McGovern, M. (2020). Competencies for industry 4.0. *International Journal on Interactive Design and Manufacturing*, 14(4), pp. 1511-1524.

[18] Hicks, C., McGovern, T. and Earl, C.F. (2000). Supply chain management: A strategic issue in engineer to order manufacturing. *International Journal of Production Economics*, 65(2), pp. 179-190.

[19] ISTAT (2022). Classificazione Delle Attività Economiche Ateco. Available at: https://www.istat.it/it/archivio/17888 (Accessed: 15 April 2022)

[20] Kanda, A. and Deshmukh, S.G. (2008). Supply chain coordination: perspectives, empirical studies and research directions. *International Journal of Production Economics*, 115(2), pp. 316-335.

[21] Kaplan, R. S., & Norton, D. P. (1996). Linking the balanced scorecard to strategy. *California Management Review*, 39(1), pp. 53-79.

[22] Malone, T.W. and Crowston, K. (1994). The interdisciplinary study of coordination. *ACM Computing Surveys (CSUR)*, 26(1), pp. 87-119.

[23] Machado, C.G., Winroth, M.P. and Ribeiro da Silva, E.H.D. (2020). Sustainable manufacturing in Industry 4.0: an emerging research agenda. *International Journal of Production Research,* 58(5), pp.1462-1484.

[24] Mello, M.H., Strandhagen, J.O. and Alfnes, E. (2015). Analyzing the factors affecting coordination in engineer-to-order supply chain. *International Journal of Operations & Production Management*.

[25] Mello, M.H., Strandhagen, J.O. and Alfnes, E. (2015). The role of coordination in avoiding project delays in an engineer-to-order supply chain. *Journal of Manufacturing Technology Management*.

[26] Mello, M.H., Gosling, J., Naim, M.M., Strandhagen, J.O. and Brett, P.O. (2017). Improving coordination in an engineer-to-order supply chain using a soft systems approach. *Production Planning & Control*, 28(2), pp. 89-107.

[27] Özbayrak, M., Papadopoulou, T.C. and Akgun, M. (2007). Systems dynamics modelling of a manufacturing supply chain system. *Simulation Modelling Practice and Theory*, 15(10), pp. 1338-1355.

[28] Patrucco, A., Ciccullo, F. and Pero, M. (2020). Industry 4.0 and supply chain process re-engineering: A coproduction study of materials management in construction. *Business Process Management Journal*.

[29] Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Engel, P., Harnisch, M., and Justus, J. (2015). Industry 4.0: The Future of Productivity and Growth in Manufacturing Industries. Available at: ttps://www.bcg.com/publications/2015/engineered_products_project_business_industry_4_future_productivity_growth_manufacturing_industries (Accessed: 15 April 2022)

[30] Sahin, F. and Robinson, E.P. (2002). Flow coordination and information sharing in supply chains: review, implications, and directions for future research. *Decision Sciences*, 33(4), pp.505-536.

[31] Tu, Y.L., Xie, S.Q. and Kam, J.J. (2006). Rapid one-of-a-kind production. *The International Journal of Advanced Manufacturing Technology*, 29(5), pp.499-510.

[32] Twigg, D., 2002. Managing the design/manufacturing interface across firms. *Integrated Manufacturing Systems*.

[33] Vaidya, S., Ambad, P. and Bhosle, S., 2018. Industry 4.0-a glimpse. *Procedia Manufacturing*, 20, pp. 233-238.

[34] Voss, C., Tsikriktsis, N., & Frohlich, M., 2002. Case research in operations management. *International Journal of Operations and Production Management, 22*(2), pp. 195-219.

[35] Yin, R. K. (2018). Case Study Research and Applications: Design and Methods (6th ed.). Sage, Thousand Oaks (CA).