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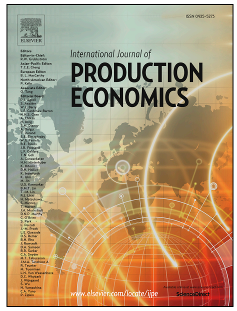

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Engineering and production decoupling configurations:

An empirical study in the machinery industry

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ABSTRACT

Engineer-to-order supply chains are traditionally considered to perform all engineering and production activities based on specific orders. However, in practice, some engineering and production activities can be speculatively undertaken to reduce the delivery lead time, thus leading to a range of decoupling configurations for both engineering and production processes. The literature rarely addresses this issue, mainly focusing on either the production or the engineering dimensions, which opens a gap between theory and practice. The purpose of this study is to reduce this gap and assess the potential impact of a unique two-dimensional customer order decoupling point (2D-CODP) framework that is inclusive of all the individual literature studies and to evaluate the managerial approaches employed in the different decoupling configurations. To achieve this aim, research using multiple case studies is conducted in the machinery industry. The key results flowing from the empirical analysis are the identification of 4 clusters of decoupling configurations chosen by the different cases and the classification of the managerial approaches employed in the specific decoupling configurations. The main contribution of this paper is that it adds insight regarding the debate on engineer-to-order definitions. Additionally, this paper enriches existing knowledge regarding the contingencies that drive the application of different managerial approaches upstream and downstream of the CODP. Finally, this paper provides cases that exemplify how to use the 2D-CODP framework, guiding managers in understanding the positioning of the product families and choosing how to manage and coordinate activities upstream and downstream of the CODP based on their positioning.

Keywords: *customer order decoupling point; engineer-to-order; supply chain management; case study; engineering and production interface.*

1 Introduction

The customer order decoupling point (CODP) is the point in a process where a product becomes associated with a specific customer order, thus separating the activities performed based on forecasts from those performed based on orders (Hoekstra and Romme, 1992; Sharman, 1984; Wemmerlöv, 1984). Companies make a choice to provide customers with a high degree of choice, i.e., flexibility, or to maintain a high degree of internal efficiency (Barlow et al., 2003), which is reflected in the position of the CODP.

In the last few decades, companies have faced the challenge of balancing flexibility and efficiency by designing and manufacturing customized products at a competitive price with short delivery lead time (Trentin et al., 2011); this is part of a general trend towards customer order-driven manufacturing (Wortmann et al., 1997). Companies have therefore reduced the elements that are made to stock, increasing coordination challenges between engineering and production processes (Mello et al., 2017). Simultaneously, there has been increasing competitive pressure towards price reduction and shortening delivery lead time in global markets, requiring companies to anticipate some engineering and production activities to forecast (Hicks et al., 2001, 2000).

To face these challenges, a strategic positioning of the CODP is proposed in the literature as the means to support companies' choices in finding the equilibrium between flexibility and efficiency (Rudberg and Wikner, 2004). Nevertheless, the traditional CODP frameworks proposed in the literature mostly apply to make-to-stock decoupling configurations, and they have been demonstrated to be too general when applied to customer-driven situations (Amaro et al., 1999; Dekkers, 2006; Gosling et al., 2017). In particular, the engineer-to-order decoupling configuration is traditionally considered to perform all the engineering and production activities based on order (Caron and Fiore, 1995; Sharman, 1984). However, engineer-to-order is more complex than this assumption: in some cases the engineering activities may not be completely driven by actual customer orders but may be undertaken speculatively based on market knowledge and technical advances (Gosling and Naim, 2009). In practice, engineer-to-order companies apply many different product standardisation strategies (Willner et al., 2016). In fact, they can decide to partially standardise the engineering work (i.e., defining part of the product structure before the customer order entry point and reusing existing designs) to increase efficiency (Amaro et al., 1999; Haug et al., 2009), as well as to produce some elements before the customer order arrives. Hence, there is a need to better understand the complex interactions between the customer-driven elements of production and engineering activities for organisations that operate in challenging engineer-to-order sectors.

Although many decoupling studies focus purely on production flows (e.g., Olhager, 2003; Sun et al., 2008), some existing studies give insight into production and engineering interactions by developing frameworks to visualise production-based COPDs and potential engineering-based decoupling points (Dekkers, 2006; Rudberg and Wikner, 2004; Wikner and Rudberg, 2005). However, the literature has proposed very different frameworks, causing confusion regarding engineer-to-order definitions and the lack of a unique and comprehensive CODP framework. In the current state, it is difficult to compare, combine or contrast the different studies. Additionally, the managerial approaches required for different configurations are not well understood, especially when seeking to integrate complex customer-driven engineering and production flows. Recent key studies have mainly focused on the engineering dimension without looking at the integration with the production one (Gosling et al., 2017; Veldman and Alblas, 2012) or considering production activities as always being performed completely to order (Willner et al., 2016). For this reason, we believe that the gap between engineer-to-order theory and practice is still significant, as noted by recent studies in engineer-to-order industries (Mello et al., 2017; Sandrin et al., 2018), and that "two-dimensional" empirical studies (i.e., those that consider interactions between engineering and production CODPs) are still limited. Empirically supported guidance is needed to help organizations consider where to position the CODP to study both engineering and production decoupling configurations and how to manage and coordinate activities based on the configuration chosen (Dekkers et al., 2013; Gosling et al., 2017; Gosling and Naim, 2009).

Therefore, the overarching research aim of the present study is to contribute to reducing the gap between engineer-to-order theory and practice by empirically investigating in an engineer-to-order industry, i.e., the machinery industry. The following are our research questions.

RQ1: What are the engineering and production decoupling configurations applied by companies operating in the machinery industry, and how do they compare with those described in the published literature?

RQ2: How do companies operating in the machinery industry manage engineering and production activities in different decoupling configurations?

To address these questions, this paper reviews and integrates the previous studies on CODP in a structured framework, including both the engineering and production perspectives. In doing so, a state-of-the-art synthesis of decoupling configurations is developed, offering a holistic and complete view of all configurations studied in the literature and the theoretically possible configurations. This framework is then empirically tested to assess its suitability in representing case studies in the machinery industry. Moreover, this study takes a contingent perspective, investigating and analysing the managerial approaches that support the different configurations, both upstream and downstream of the CODP. In this way, this paper contributes to the theoretical debate on engineer-to-order definitions and appropriate strategic choices, as well as supporting managers operating in engineer-to-order companies who seek to control and coordinate engineering and production processes.

The remainder of this paper is organized as follows. In section 2, the review of the CODP literature is provided; in section 3, the methodology applied is described; in section 4, the results of the study are presented; in section 5 the findings are discussed; in section 6, the paper concludes providing limitations and further research opportunities.

2 Literature Review

2.1 Engineering and production decoupling configurations

Decoupling and order penetration concepts have been widely discussed over the years in the literature in different streams of research (e.g., logistics and manufacturing, information systems, mass customisation, etc.). Table 1 presents the analysis of the key works that have studied decoupling configurations in the production and/or engineering process.

------- *PLEASE INSERT TABLE 1 HERE* -------

The seminal papers are all conceptual studies that define the CODP as a means to decouple the production process into sub-flows. Some of these works completely exclude the engineering process (Hoekstra and Romme, 1992), considering it as not relevant from a material flow perspective. Others include the engineering process as a sub-flow that precedes production and cannot be decoupled (Sharman, 1984; Wortmann, 1992). Over the years, the CODP frameworks were further analysed and empirically assessed, demonstrating that the engineering process can be decoupled into sub-flows; companies make decoupling decisions along both engineering and production dimensions (Amaro et al., 1999; Duray et al., 2000; Giesberts and van der Tang, 1992; Lampel and Mintzberg, 1996; Muntslag, 1993; Oden et al., 1993; Winch, 2003).

Building on this, a “two-dimensional” (2D) CODP perspective has been introduced by conceptual (Wikner and Rudberg, 2005) and empirical (Dekkers, 2006) studies, wherein engineering and production are considered as different flows of activities that can be “decoupled” independently. Thus, different engineering and production decoupling configurations (i.e., tuples of CODP positioning along the engineering and production processes sub-flows) were identified along with the interfaces between them.

The 2D-CODP perspective supports the analysis of the engineering process sub-flows (Gosling et al., 2017; Willner et al., 2016) or, more generally, of the customisation strategies (MacCarthy, 2013; Semini et al., 2014) of companies operating in contexts characterised by high customisation and variety (e.g., capital goods, construction, etc.).

However, investigating the literature about the decoupling strategies employed in different industrial realities revealed ambiguous definitions and a lack of an overall common structure in the theory related to decoupling points (Wikner, 2014). Therefore, this study needs to analyse and merge the existing literature and industrial case studies to a single and comprehensive framework, which is the focus of RQ1. This framework is proposed in Figure 1, including all the production and engineering decoupling configurations identified over the years in the literature.

------- *PLEASE INSERT FIGURE 1 HERE* -------

The vertical axis of figure 1 indicates the engineering process sub-flows, i.e., the main activities of the engineering process: (i) Research the product concept; (ii) Develop codes, standards and principles (e.g., materials to use, performance expected in different conditions); (iii) Design detailed product specifications; (iv) Modify existing designs with major changes (i.e., technical/functional characteristics); (v) Modify existing designs with minor changes (i.e., superficial characteristics); (vi) Combine a set of pre-defined design options. The horizontal axis of figure 1 indicates the production process sub-flows, i.e., the main activities of the production process: (i) Purchase raw materials; (ii) Make parts/subassemblies; (iii) Assemble of parts/subassemblies; (iv) Deliver finished product.

2.2 Differentiating managerial approaches for decoupling configurations

With the introduction of the decoupling concept, the literature underlined that there is a fundamental difference between the priorities upstream and downstream of the CODP, which is led by distinctive drivers, i.e., forecast-driven vs order-driven (Hallgren and Olhager, 2006;

Olhager, 2012, 2010; Verdouw et al., 2008). As a consequence, the CODP positioning affects the choice for different managerial approaches that can support the activities performed before and after the customer order entry point.

Different debates have been encountered over the years in the literature. From the 1980s to the 1990s, the debate was related to managerial approaches able to support the single company in achieving manufacturing process efficiency and effectiveness (Benton and Shin, 1998; Hayes and Wheelwright, 1984; Hoekstra and Romme, 1992; Wemmerlöv, 1984; Wortmann, 1992). From the end of the 1990s to the beginning of the 2000s, in accordance with the evolution of supply chain management literature (Stevens and Johnson, 2016), the debate was enlarged to managerial approaches to support the supply chain in achieving efficiency and effectiveness by introducing the concepts of leanness, agility and leagility (Aitken et al., 2002; Christopher, 2000; Christopher and Towill, 2001; Mason-Jones et al., 2000; Naylor et al., 1999). From the middle of 2000s to the current day, the debate was further enlarged to include the managerial approaches to support the engineering process in achieving efficiency and effectiveness (Chen, 2006; Danese and Romano, 2004; Dekkers, 2006; Rudberg and Wikner, 2004; Salvador et al., 2007; Semini et al., 2014; Veldman and Alblas, 2012; Wikner and Rudberg, 2005). These studies rely on the 2D-CODP framework to investigate the possibility of decoupling both the production and the engineering processes.

In Table 2 the detailed analysis of these studies is provided.

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Summarising the main contents of the studies analysed, it can be said that the priorities of companies upstream and downstream of the CODP have a common point: they are focused on creating the conditions to successfully fulfil the order in accordance with customer expectations and considering all the processes constraints (Rudberg and Wikner, 2004). When the engineering and production activities are performed to forecast upstream of the CODP, the constraint is the availability of designs and materials and the priority is to assure it at the right moment and in the correct quantities, avoiding stock holding costs (due to physical space occupied, obsolescence, perishability, etc.). Whereas, when activities are performed based on a specific customer order downstream of the CODP, the constraint is the engineering and production capacity (a combination of engineering and production lead times and current load of engineering and production resources) to fulfil the customer requirements and react quickly to variations through rapid reconfiguration of the engineering and production processes.

As a consequence, the decoupling configuration chosen, i.e., the extent of engineering and production activities performed to forecast and to order, can influence the way the company manages the processes (Gosling et al., 2017; Van Donk and Van Doorne, 2016). When the decoupling configurations are purely driven by forecasts (i.e., all activities performed upstream of the CODP) or orders (i.e., all activities performed downstream of the CODP), the lean and agile principles, respectively, are the dominant philosophies driving managerial approaches. According to Naim and Gosling (2011) and Ciccullo et al. (2018), the lean principle employs continuous improvement efforts to develop a value stream to eliminate all waste (including time) or non-value steps along the supply chain; agile principles employ market knowledge, resource and inventory pooling and/or redundancy, to be responsive and flexible for the customers while hedging the risk of supply shortage or related to upstream disruptions. Whereas, when the decoupling configurations are hybridised, i.e., some activities are performed upstream and some downstream of the CODP, a mix of lean (mainly upstream) and agile (mainly downstream) approaches is needed, i.e., the leagile principle, to strongly leverage the interfaces between engineering and production before and after the customer order entry point.

Despite the increasing focus of the literature on the 2D-CODP framework over the years, most engineer-to-order studies still consider the difference between the engineering decoupling configurations as irrelevant from a managerial perspective and analyse the managerial approaches without looking at the 2D-CODP positioning. In the next sub-section, these studies are briefly analysed.

2.3 Recent engineer-to-order studies on managerial approaches

A number of recent studies provide managerial insights into engineer-to-order supply chains. Product development has been further analysed, e.g., methods to improve the product structure (Jansson et al., 2014; Johnsson, 2013), product configuration systems (Shafiee et al., 2014), product modularity and supply chain integration (Pero et al., 2015). Techniques for performance improvement have been identified; they are based on principles such as synchronization, time compression and information transparency (Gosling et al., 2015). Further engineer-to-order studies have emphasised production planning and control techniques, such as project planning and capacity planning (Adrodegari et al., 2015; Carvalho et al., 2017, 2015; Rossi et al., 2017), as well as design management and bottleneck management extension to product design and engineering processes (Hinckeldeyn et al., 2014; Wesz et al., 2018). The application of lean practices such as customer involvement and partnership, standardisation, lean purchasing, etc., has been demonstrated to be meaningful if the challenges provided by the engineer-to-order context are taken into account (Birkie and Trucco, 2016; Cannas et al., 2018a). Finally, the main causes of a lack of coordination have been analysed (Mello et al., 2015a, 2015b), and mechanisms such as collaboration with suppliers and development of production capabilities have been proposed (Mello et al., 2017).

All these studies need to be validated in the various decoupling configurations, as proposed in Figure 1, to understand what delimits the application of the different managerial approaches (Cannas et al., 2018b). Given the recent interest in engineer-to-order supply chains, it is a good time for a synthesis of the managerial approaches viz-a-viz possible decoupling configurations and reflection on the gap between practice and research. Therefore, this study is needed to investigate the way companies in the machinery industry manage activities in different engineering and production decoupling configurations; this is the focus of RQ2.

3 Methodology

This paper aims to reduce the gap between theory and practice by empirically validating and extending the insights derived from the literature. In line with this aim, an exploratory multiple case study research has been conducted to empirically explore and fully understand the nature and complexity of the phenomenon guiding engineering and production decoupling choices.

3.1 The context analysed

To limit the analysis and increase the control of variations within the population (Eisenhardt, 1989), this paper focuses on one industry in one country: the Italian machinery industry. In this industry, the flexibility provided is high and the customer is engaged from the early engineering phases. There are many requirements for customisation, and design updates and reworks are typical. Companies operating in this industry are also facing intense competition in global markets, and there is a perceived need to increase standardisation to enhance efficiency due to price pressures from low-cost locations. Despite this, Italy is among the top countries in the global market in terms of export and production activities in the machinery industry; it has been incredibly resilient during recent years and has grown while many other sectors were weakening (Federmacchine, 2017). This makes this industry particularly interesting to study. Therefore, the concern of this study is to understand the engineering and production decoupling configurations that companies operating in the Italian machinery industry are applying and the insights that can be gained by comparing theory and practice. Further, the managerial approaches applied by these companies are analysed and classified. Since it is possible to find more than one decoupling strategy within the same company, the focus of the study is on the primary decoupling configuration chosen by the company, and the unit of analysis is the product family representative of the core business (i.e., the one that impacts more than 60% of the company's turnover).

3.2 Case selection

For the selection of cases, the researchers decided to start with well-known companies with good performance records (Stuart et al., 2002). The complete list of companies operating in the Italian machinery industry was found in the database AIDA (https://aida.bvdinfo.com/). Only medium and large companies were selected to ensure that both engineering and production processes and strategic initiatives could be analysed comprehensively. Because of this, the classification proposed by the European Commission (EU recommendation 2003/361) was adopted. Then, cases were selected to obtain both literal replication, i.e., cases with similar decoupling configurations, and theoretical replication, i.e., cases with different decoupling configurations (Yin, 2009). This permits the replication of findings across cases and distinguishes them based on the main contrasts observed (Miles and Huberman, 1994). In particular, case selection was performed to ensure the maximum variation within the population in the dimensions of relevant interest (Seawright and Gerring, 2008), i.e., the engineering and production decoupling configurations, and to find subgroups to compare and identify common patterns. Within the list identified, the inclusion of companies in the sample was based on the decoupling strategy expected to be followed by the companies for the core product family. Since the choices for the CODP positioning have been demonstrated to depend upon the market, product and processes characteristics (Olhager, 2003), the expectation was that companies belonging to different sectors (e.g., plastic and rubber, machine tool) and those designing and producing different products (e.g., extruders, laser cutting, confectionery lines) would choose different engineering and production decoupling configurations. The needed information was taken from public data available on the companies' websites and reports developed by national industrial associations (UCIMU, Amaplast, etc.), the Italian National Institute of Statistics (ISTAT) and universities or consultancy companies; it was also obtained from private data available thanks to the authors' experience in the machinery sector during previous research projects. In total, a set of 11 companies was selected, all recognised to be market leaders in terms of turnover (i.e., the companies are included among the top 20 companies with the highest turnover in the Italian statistical classification of their economic areas, i.e., machinery and equipment manufacturing). In Table 3, a case study overview is provided.

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3.3 Data gathering and analysis

The data gathering phase was conducted to observe and understand the phenomenon while preserving any possible different or contradictory view of what is happening (Stake, 1995). The focus was on assuring that data were collected through multiple sources to enable triangulation of evidence (Hays, 2004). The data sources for all the cases were: (i) face-to-face interviews addressed to experts or group of experts (based on the preferences expressed in terms of confidentiality); (ii) direct observations; (iii) official documents; (iv) internal documents; (v) phone interviews, when needed, to complete missing data and/or verify conclusions.

The case study protocol, provided in Table 4, supported the data collection in all its phases. The questionnaire for the interview phase was defined based on a semi-structured approach, i.e., open questions to address the main constructs of the study with a formal protocol while creating a rich dialogue and leaving the interviewees free to discuss including all the possible information, which is not easy to be predicted in advance (Yin, 2009). Each interview lasted four hours on average. The participants were always managers or a group of managers (depending on the company's availability and their organizational chart) with greater than 15 years of experience in the machinery industry, sometimes in more than one company. They were all involved in the engineering and production processes (e.g., engineering manager, operations manager, plant manager).

The participants described the product family representing the core business of the company. With respect to a specific product family, the amount and nature of engineering and production activities performed upstream and downstream of the CODP was described. Moreover, participants described the ways the company manages activities upstream and downstream of the CODP and why. Finally, according to Sousa and Voss (2008), the performance outcome was included in the analysis as dependent measure to assess the fit between the strategic choice of the company (i.e., the engineering and production decoupling configurations) and the use of practices (i.e., the managerial approaches). According to the CODP literature (Dekkers, 2006; Dekkers et al., 2013; Gosling et al., 2017; Hoekstra and Romme, 1992; Olhager, 2003; Rudberg and Wikner, 2004; Sharman, 1984), the performance outcome includes: delivery, price, quality and flexibility. In particular, in the machinery industry context, the quality is measured based on the "technology", i.e., the uniqueness of the technology, designed together with the customer according to specific needs, and the "reliability", i.e., low risk for early unexpected defects after sales. Due to companies' information privacy and data protection law, the only way to measure companies' performance outcome was a qualitative assessment. Therefore, the companies interviewed qualitatively evaluated their position in the market with respect to the performances analysed, based on a 5-points ordinal level scale (0 – not competitive, 1 – low competitive, 2 – on market average, 3 – competitive, 4 – very competitive). For example, a company that positioned itself as 4 in technology and flexibility and 0 in price, delivery and reliability is a company that is market leader in technology and flexibility, able to target customers that search for high innovative and tailored-made products, but very low competitive in price, delivery and reliability, not suitable for either cost-conscious or time-sensitive customers.

Once the data were collected, pattern matching was adopted as the analytic technique, which consists of, according to Yin (2009), comparing the empirically based patterns with the predicted ones that correspond to theories grounded in the literature. In particular, according to the research questions in this study, the case study research seeks to understand, in accordance with Stuart et al. (2002), if the existing theoretical models reasonably explain the behaviour observed in the cases. The literature review performed in the previous section provides a conceptual starting point for potential configurations or decoupling patterns and managerial approaches to apply upstream and downstream of the CODP. The final goal is to identify the validity of the existing framework considering the frequency of occurrence in the empirical data, extending and refining them accordingly. In practice, the researchers performed data analysis and triangulation, which included positioning each case on the engineering and production decoupling configurations framework, verifying the positioning in the framework through team discussions, classifying the managerial approaches and comparing with other cases.

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4 Results

4.1 Engineering and production configurations

In figure 2, the production and engineering decoupling configurations for each case study have been mapped onto the framework developed in Figure 1.

------- *PLEASE INSERT FIGURE 2 HERE* -------

The analysis of the combination of the engineering and production decoupling choices shows that the companies interviewed favour intermediate configurations for the product families that represent their core business. In the vertical axis of figure 2, all the activities identified in the literature as engineering process sub-flows, from “research” to “combine”, were found to be suitable to describe the context analysed. A part of this, in the sample, is always performed to forecast, i.e., research, development and design. This is because prototypes of new products are presented to customers during industrial fairs (e.g., Plast, BI-MU, Euroblech, Emo). Based on the feedback received from such exhibitions, a final version of the new product is released and inserted into the catalogue. Therefore, a generic Bill of Materials (BoM) is used to forecast and is composed of a set of design options, i.e., different components with different functionalities; it is adapted, after the customer order entry point, with major (cases C1, E1, F1, G1, H1, I1) or minor (cases A1, D1, K1) modifications, or simply finalized through selection and combination of the existing variants in a final structure (cases B1, J1). According to case H1: "*we define a product catalogue and the sales managers act on it to negotiate with the customer […] However, modifications in the product BoM are always required by the customer during negotiation, and components could be added, adapted, or removed after the order*". Interviewees do not consider the possibility of performing all the engineering activities based on forecast because engineering work is always required, to some extent, after the order. According to case C1: "*Full standardisation could reduce our profits. For example, we could draw a narrow range of technical solutions, instead of customising them; but then, this means giving the customer a much better-performing machine than the one requested but supplying it at the price of the lesser one. Is it worth it?*". In the horizontal axis of figure 2, empirical evidence suggests an additional production process sub-flow, i.e., finalize. Despite some traditional make-to-order (cases C1, I1) and assemble-to-order (cases B1, J1) configurations, most of the cases (cases A1, D1, E1, F1, G1, H1, K1) decouple manufacturing activities: they make generic parts/subassemblies to stock and finalize specific parts/subassemblies to order. In the case studies analysed, the strategic components (key parts of the machine with high utilisation rate) and the critical components (complex parts of the machine with long production or procurement lead time) are the generic parts/subassemblies. Whereas, specific parts/subassemblies are the customised components (parts of the machine that are usually different from one customer order to another). For example, according to case A1: "*Strategic components are the bearings. We always need some of them in stock because we use 8 bearings per bender and produce about 40 benders a year. Additionally, we use them as spare parts for repair […] Critical components are the shoulders: they have a procurement lead time equal to 6 months, almost as long as the entire order project (10 months). Thus, we need to start the production activities for these parts to forecast […] Customised components are the electrical components such as sensors and cables. The customer, for example, can ask for 6 different types of sensors, 20 different brands, 20 different standards (depending on the destination, regulations change). Also, the cables change depending on the layout of the customer's plant*".

The results obtained are aligned with previous literature studies, such as Dekkers (2006) and Hinckeldeyn et al. (2014), which defined the design novelty and customisation of the modules (i.e., basic, standard, optional or special modules) as main sources of differentiation in the engineering process in terms of efforts required to fulfil an order. Thus, by analysing the two axes and triangulating the empirical results with the literature, four main decoupling configurations were identified for the case studies analysed based on the strategy employed for providing the core product families to the market; they can be defined as follows:

- **Special machines**: Upstream of the CODP, the research, development and design activities are performed so that the product family can be proposed in the catalogue; in these cases, the choice is to keep the catalogue nonspecific and not anticipate any manufacturing activity. Then, downstream of the CODP, major design modifications (e.g., technical/functional changes to the spindles or the tools) are applied to most of the existing components according to customer requirements (on average, between 50% and 70% of the product BoM after the customer order entry point), and the components (generic and specific) are produced to order (cases C1, I1);

- **Customised machines**: Upstream of the CODP, the research, development and design activities are performed so that the product family can be proposed in the catalogue; in these cases, the choice is to provide some standard options in the catalogue to partially guide the customers and anticipate the manufacturing activities of generic components. Then, downstream of the CODP, major design modifications are applied to the specific components (on average, between 20% and 40% of the product BoM), and these are then produced to order (cases E1, F1, G1, H1);
- **Standard customised machines**: Upstream of the CODP, the research, development and design activities are performed so that the product family can be proposed in the catalogue; in these cases, the choice is to provide many standard options in the catalogue to intensely guide the customer and anticipate manufacturing activities of generic components. Then, downstream of the CODP, minor design modifications are applied to the specific components (e.g., colour or layout changes), and these are then produced to order (cases A1, D1, K1);
- **Modular machines**: Upstream of the CODP, the research, development and design activities are performed so that the product family can be proposed in the catalogue; in these cases, the choice is to provide only standard options in the catalogue to completely guide the customer and anticipate all the manufacturing activities of components. Then, downstream of the CODP, the existing designs are combined in a final product structure according to the customer requirements, and the components already produced are assembled to order (cases B1, J1).

4.2 Managerial approaches employed by different decoupling configurations

The managerial approaches identified through the case studies are summarised in Table 5.

------- *PLEASE INSERT TABLE 5 HERE* -------

Upstream of the CODP, based on the data analysis and triangulation with the literature, it can be seen that the managerial approaches are applied to pursue three priorities, which drive the activities performed to forecast to achieve the successful fulfilment of the order in accordance with customer expectations. Priority 1 is to assure the availability of the needed designs in the repository (i.e., database where data are stored and managed) when the customer order arrives so that the number of engineering activities performed after the order are only those that add value to the final product. This is possible thanks to the correct use of historical data, low data redundancy and high data quality, as well as appropriate marketing analysis and the right design options/rules. For this reason, the managerial approaches supporting this aim are: (i) data management systems, which "*aid the engineers to quickly search for data and estimate costs and lead times thanks to well-organised storage without redundancy and with high traceability*" (case E1); (ii) standard-work procedures, which "*help engineers to follow specific steps when designing the products, reducing variability and increasing quality of the designs*" (case A1); (iii) modular design, which "*helps to increase the product reconfigurability and anticipate production activities before the arrival of the customer order, adapting them more quickly to different requirements*" (case G1).

Priority 2 is to assure the availability of the needed materials when the customer order arrives so that the number of production activities performed after the order are only those that add value to the final product. This is possible thanks to well-organised planning and control of production activities and the reduction of waste, lead times and errors along the production process. For this reason, the managerial approaches supporting this aim are: (i) special contracts with suppliers, which "*help in reducing procurement lead times. We have a special contract with the supplier to keep a couple of rough shoulders always in stock. Therefore, the procurement lead time after the order is one month instead of six*" (case A1); (ii) lean manufacturing, which "*allows synchronizing the entire supply chain with JIT techniques, respecting the takt-time and keeping the production levelled*" (case F1); (iii) rolling MRP, which "*assures the availability of materials since generic modules start to be made to forecast and, when a customer order arrives, the MRP automatically changes according to the delivery dates, supplier plan, etc.*" (case D1).

Priority 3 is to assure the engineering and production coordination upstream of the CODP so that the amount of engineering and production interactions performed after the order are only those that add value to the final product. This is possible thanks to the anticipation of engineering and production constraints, the functions alignment to the same global goal, i.e., the product value, and a smoothed order fulfilment process. For this reason, the managerial approaches supporting this aim are: (i) inter-functional teams, i.e., which "*employ synergies between different functions to define strategic targets and goals, especially in the research and development phase, and achieve them*" (case B1); (ii) early supplier involvement, which "*exploits the high competences and experience of the suppliers to design components in the most efficient possible way*" (case J1); (iii) concurrent engineering, which "*focuses on making the design fit to purpose before the customer order arrives, thanks to the involvement of all the engineering functions in a unique machine development project*" (case K1).

Downstream of the CODP, based on the data analysis and triangulation with the literature, it can be stated that the managerial approaches are applied to pursue three different priorities that drive the activities performed to order to achieve the successful fulfilment of the order in accordance with customer expectations. Priority 4 is to assure the engineering capacity and capability to satisfy the customer requests. This is possible thanks to a well-balanced engineering workload and good engineering knowledge management. For this reason, the managerial approaches supporting this aim are: (i) workload balancing, "*we can define targets in terms of the engineering lead times and costs for a project, and if the customer requires specific customisation after the order, additional costs and times can be easily included*" (case H1); (ii) engineering knowledge management, because "*the know-how and experience of the single resources must be shared and transmitted to the entire department to be* *responsive and quick in managing unexpected changes and specific customer requests*" (case I1)

Priority 5 is to assure the production capacity and capability to satisfy customer requests. This is possible thanks to a well-balanced production workload, the avoidance of under- or over-productivity, and the needed flexibility of the production resources. For this reason, the managerial approaches supporting this aim are: (i) vertical integration because "*the internal production of the core parts ensures maximum flexibility and increases control to quickly manage priorities and increase the ability to react to unexpected changes*" (case D1); (ii) late change management, because "*if you know what to expect, you can react faster to the requirements for changes and reduce the impact on lead times*" (case E1).

Priority 6 is to assure the coordination between engineering and production downstream of the CODP. This is possible thanks to the interfaces between the two processes that detect and solve problems in real-time and assure the global control of activities. For this reason, the managerial approaches supporting this aim are: (i) project management expertise, which involves "*a specific cross-functional role, the project manager, to control the entire project, coordinate project activities and identify problems when they occur*" (case F1); (ii) daily meetings, "*to increase integration between engineering and production departments, detect problems when they occur and solve them in real time*" (case G1); (iii) engineering and production overlap, which "*is useful especially for those components that have long production lead times, like the reducers, which are immediately designed and produced after the order without waiting for the engineering work to be finished*" (case C1).

4.3 Performance outcomes

In the cases analysed, we observed that the fit between the decoupling configurations and the managerial approaches is focused on assuring the successful fulfilment of the order in accordance with customer expectations, which are related to four main performance outcomes:

time, price, flexibility, uniqueness of the technology and reliability. The priorities of the companies interviewed on specific performance outcomes brought them to locate the customer order entry point in different phases of the engineering and production processes, i.e., the decoupling configuration. However, the effective achievement of the desired performance, according to the companies interviewed, is possible only if the decoupling configuration is supported by suitable managerial approaches. Therefore, the choice of the managerial approaches explained above is driven by a set of engineering, production and coordination needs, upstream and downstream of the CODP, which are different for each decoupling configuration, determined by specific desired performance outcomes. The results of this analysis are depicted in Figure 3, which shows the performance outcomes of the different decoupling configurations chosen by the cases analysed, as well as the link with priorities and the proposed focus of the managerial approach.

------- *PLEASE INSERT FIGURE 3 HERE* -------

5 Discussion of findings

In this section the cases are discussed in relation to the classification in the 2D-CODP framework and the approaches employed to manage and coordinate engineering and production processes upstream and downstream of the CODP, which appear to be contingent upon the decoupling configuration.

5.1 Comparing managerial approaches with decoupling configurations

By comparing the upstream managerial approaches with the decoupling configurations, it can be seen that some of them are common to all cases, i.e., data management systems and inter-functional teams. These approaches are considered fundamental for all configurations since no configuration performs research, development and design completely to order. They design from already developed codes, standards and principles, or modify designs to some extent. Other approaches, i.e., modularity, rolling MRP, lean manufacturing, special contracts with supplier and early supplier involvement, are considered significant for configurations that start the production activities of generic components before the order and therefore are excluded from the "special machines" configuration. These practices and techniques allow companies to assure the availability of materials even when there is still uncertainty in the finished product. Standard-work procedure and concurrent engineering, on the other hand, are considered relevant when the amount of engineering work after the order requires only minor changes, i.e., “standard customised machines”, or when combinations of existing designs, i.e., “modular machines”, are made after the order.

By comparing the downstream of the CODP managerial approaches with the decoupling configurations, workload balance is underlined as relevant for all cases in which major or minor modifications to the designs are applied and a certain amount of design work is needed after the order, i.e., "special machines", "customized machines" and "standard customized machines". Additionally, for configurations where new design or major changes are needed, exploitation of the knowledge and experience of the entire department is required to carry out the work quickly and effectively. As far as vertical integration concerns, it is considered fundamental for the two configurations that produce generic components to forecast and finalize specific components to order, i.e., “customised machines” and “standard customized machines”. The two configurations that apply major modifications, i.e., “special machines” and “customized machines”, underline the importance of project management, daily meetings and the overlapping of the two processes. These techniques help in facing the numerous challenges that involve both the design of the product and the product itself during the development of a project after the order. Additionally, these configurations need to manage the high variability of the single customer demand after the order through late change management.

5.2 *Comparing performance outcome with decoupling configurations and managerial approaches*

In analysing the results in terms of performance outcome (Figure 3), it can be observed that, when the engineering and production activities are mostly performed after the customer order entry point (i.e., special machines, cases C1 and I1), the performance outcome is the capability to always meet customer requirements for customisation and provide high technological innovation. The company offering this product family leverages high flexibility and technology at the expense of the price (on average 30% higher than the market average) and delivery lead time (on average 10 months). In this case, most of the engineering, production and procurement activities are performed for the first time, with a consequent risk of unexpected defects after sales. The capacity of the engineering and production departments to answer every customer need, as well as their strong coordination downstream of the CODP, are priorities to reduce unexpected design updates, reworks and late defects as much as possible, as they cause delays and additional costs. For these reasons, the managerial approaches employed in this case are mainly focused on planning the engineering workload and leveraging engineering knowledge, assuring the responsiveness of production in reacting to the dynamic variety of a single customer order, real time activities planning and concurrent execution of engineering and production activities.

Vice versa, when the engineering and production activities are mostly performed before the customer order entry point (i.e., modular machines, cases B1 and J1), the company aims to find a market of customers that need conventional machines; competition is very high, and competitive prices are required (on average, 30% lower than competitors), as well as short lead times (customers expect product delivery in 1-2 weeks). The risk for defects is almost null because this family exploits mature technologies, but this means that the machines almost never meet requirements for customisation and there is a low degree of innovativeness. The availability of the designs and materials at the right moment and in the right quantities in addition to the strong coordination of engineering and production upstream of the CODP are the priorities for reducing the risk of exceeding the stock holding costs due to obsolescence, excessive space occupation, perishability, etc. or facing stock-outs. For these reasons, the managerial approaches employed in this case mainly focus on having high quality reference data and a good forecast-based materials planning, which involves all departments in research and development and in the detailed design, easy mix and match product design, building a reliable and efficient supply network in advance, involving external stakeholders in the detail design and formalising an engineering procedure.

Finally, intermediate strategies (customised machines, cases E1, F1, G1 and H1, and standard customised machines, cases A1, D1 and K1) allow the companies to achieve a good compromise between different competitive priorities, and the managerial approaches address a mix of upstream and downstream priorities.

5.3 Analysing the evolution of the decoupling configurations

The last stage of the study has addressed the deep understanding of the dynamics driving the decision-making process to define the optimal 2D-CODP positioning and the consequent managerial approaches. The results show that companies interviewed chose very different decoupling configurations. They also stated that their decoupling choices changed over the years, according to the dynamic changes in performance requests coming from their customers.

During the 90's, the market was characterised by similar expectations and the competition for companies operating in the Italian machinery industry was mainly driven by the creativity and capabilities of the engineering work. Accordingly, flexibility and technology were considered the only two key factors to successfully fulfil customers' orders. Thus, the product families of all the companies interviewed were belonging to the same decoupling configuration: designing and making new products for each customer completely to order.

Over the years, the fast growth and innovation in technologies and the continuous entrance of new players in the global market brought changes in the customers tastes. The companies operating in the Italian machinery industry moved in a very unstable and unpredictable environments, populated by numerous consumers with different expectations. Thus, flexibility and technology were no longer the only sources of competitive advantage and other criteria were considered essential for many companies to satisfy customers needs.

For this reason, the companies interviewed revised their strategic objectives in different ways, based on the market segment addressed. Accordingly, they shifted the customer order entry point to align the performance outcome to the customers' requests, choosing different engineering and production decoupling configurations and managerial approaches. These findings empirically support and further clarify the strategic role of the 2D-CODP, emphasised by the CODP and engineer-to-order literature over the years (Dekkers, 2006; Dekkers et al., 2013; Gosling et al., 2017; Gosling and Naim, 2009; Johnsen and Hvam, 2018; MacCarthy, 2013; Schoenwitz et al., 2017; Wikner and Rudberg, 2005), in supporting the decision-making process of companies operating in the unstable and changing engineer-to-order environment.

5.4 Practical model for choosing decoupling configurations

The findings of this study can be operationalised in a model to support managers in defining the decoupling configuration most suitable for the company's performance objective. Additionally, it can be considered an aid for managers to identify the proper managerial approaches to employ for the successful achievement of their goals. Bringing together different elements of the paper, a practical model has been developed in Figure 4 to guide practitioners. The model is based on 4 main steps:

1. The first step is based on the definition of the strategic objectives of the company in terms of performance, with reference to a specific product family and its desired positioning in the market. In doing so, the company must consider the presence of trade-offs between efficiency and flexibility performance, i.e., an operation cannot excel simultaneously on all performance measures, and define what key performance will be vital for the product family to be successful and focus on it. The map of performance outcomes developed in Figure 3 can be considered a practical guide to help managers in understanding the potential trade-offs.
2. The second step is based on the identification and implementation of the most suitable engineering and production decoupling configurations among the ones proposed in Figure 2. In doing so, the company must consider that the performance outcome is affected by the number of engineering and production activities performed after the order entry point. Figure 3 can be helpful to better understand this correlation among the two variables.
3. The third step is based on the identification and implementation of the proper managerial approaches downstream and upstream of the CODP, so that to fit the decoupling configuration. In doing so the company must consider that the decoupling configurations correspond to different engineering, production and coordination needs that should be satisfied in order to achieve the desired performance outcome. Figure 3 specifies these needs and, accordingly, Table 5 proposes a set of managerial approaches to employ in different decoupling configurations, upstream and downstream of the CODP.
4. The fourth step is based on monitoring and control the alignment between the performance outcome and the performance requested by the customers, so that to quick react to changes in customers' expectations when they are revealed. When misalignments are discovered, e.g. the flexibility that the company is able to

provide with its product family is different from the flexibility requested by the customers, managers should revise the strategic objectives, thus choosing a different decoupling configurations in the 2D-CODP framework and, accordingly, employing different managerial approaches to satisfy the new customers' needs.

------- *PLEASE INSERT FIGURE 4 HERE* -------

6 Conclusions

The purpose of this study was to reduce the gap between theory and practice and assess the potential impact of a unique 2D-CODP framework that is inclusive of all the individual literature studies and to evaluate the different managerial approaches employed in the different decoupling configurations.

6.1 Theoretical implications

From a theoretical perspective, the first contribution of this paper is that it improves the understanding of engineer-to-order strategic decoupling choices and adds insights to the debate on engineer-to-order definitions. To answer RQ1, this study provides a structured 2D-CODP framework, which improves the replicability and comparability of the existing 2D-CODP studies. We analysed the relevant studies in the CODP literature, focusing on the increasing interest in the engineering perspective (Dekkers, 2006; Gosling et al., 2017; Wikner and Rudberg, 2005; Willner et al., 2016) and compared them to the machinery industry cases. Through the analysis of a selected group of companies, four different engineering and production decoupling configurations were identified: special, customised, standard-customised and modular machines. The results obtained from the literature review and the case study research show the validity of the framework developed in classifying different decoupling configurations employed by companies operating in the machinery industry and mapping the evolution of the engineering and production decoupling configurations in the engineer-to-order context, where customers tastes are evolving over the years. Indeed, adding one sub-flow in the production process allowed the researchers to identify two additional configurations with respect to the previous literature, enriching the number of possible decoupling strategies that can be used to describe engineer-to-order companies.

Moreover, the 2D-CODP framework developed in this paper allowed the categorization into specific decoupling configurations and the identification of patterns in the case studies analysis, leading to interesting insights and generating additional contributions. We analysed patterns in the relationship between the decoupling configurations and the managerial approaches applied by the case studies upstream and downstream of the CODP. The managerial approaches identified correspond to many of those proposed in the recent engineer-to-order literature, such as lean manufacturing (Birkie et al., 2017; Birkie and Trucco, 2016; Cannas et al., 2018a), supply chain coordination (Mello et al., 2017, 2015a, 2015b), modular design (Johnsen and Hvam, 2018; Pero et al., 2015; Schoenwitz et al., 2017), etc. In addition, the results promote better understanding of the contingencies driving their application, demonstrating the importance of including the degree of engineering and production standardisation and their interfaces when designing managerial approaches. Therefore, this study also contributes to the CODP literature, which, until now, did not specify which approach is suited for a particular decoupling configuration, and has mainly focused on only either the production process or the engineering process.

Finally, through the study of the performance outcomes in the different decoupling configurations, this research revealed that the decision-making process in terms of engineering and production decoupling configurations is driven by the strategic objectives of the company in terms of performance. The desired performance outcome changes based on customer requests and can be successfully achieved only with the application of the proper decoupling configuration and its alignment with suitable managerial approaches. Thus, the third contribution of this study is the introduction of a contingency-based view, which makes it possible to understand what are the dynamics driving the choices of different engineering and production decoupling configurations and the application of different managerial approaches.

6.2 Managerial implications

From a managerial perspective, the main contribution of this paper is that it provides cases that exemplify how to use the 2D-CODP framework and how to compare the different engineering and production decoupling configurations. The framework proposed has been adjusted to the machinery industry and the results show that the strategic decisions in this industry, as in many other engineer-to-order industries, are comparable to a pendulum, continuously suspended between the opposing engineering and the production needs. A trade-off must be found between them to achieve an overarching goal, i.e. the alignment of the performance outcome with the performance required by the customers; otherwise, local needs are prioritised, and global optimisation cannot be achieved.

Also, a practical model has been developed by bringing together the different insights of the theoretical and empirical study. The model, provided in the previous section (Figure 4), can be used as a guide for managers in understanding the proper positioning of the product families in the 2D-CODP framework, according to strategic objectives, and how to manage and coordinate activities upstream and downstream of the CODP accordingly.

6.3 Limitations and further research

As with any other study, some limitations must be taken into account in this case, and the proposed framework needs to be further strengthened to increase the generalisability of the results. Despite the fact that the framework was built considering studies conducted in other industries (e.g., construction in Gosling, Hewlett, and Naim 2017; shipbuilding in Semini et al. 2014), empirical validation has only been conducted using a restricted number of cases in one specific industry. Additionally, some of the managers interviewed had worked only for one company, so they had a limited view of their company and their competitive environment. For these reasons, further research is considered fundamental; it should apply different methodologies, such as survey-based research and quantitative models, address different sectors, such as aerospace, and different contexts, including also non-engineer-to-order ones to cover different configurations in the framework. Moreover, since we focus only on the decoupling configuration of the core product family, further research will be devoted to investigating different choices in terms of the combination of decoupling points. Finally, the challenges in the data collection related to information privacy and data protection law made necessary to do a qualitative assessment of the performance outcome, decreasing the replicability of the results and reducing the reliability of this study. The possibility to access to companies' quantitative data is very low and there are no recent studies addressing a reliable performance measurement method for case study research. Therefore, further research is needed in this direction.

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Table 1. Literature review of key studies related to engineering and production decoupling configurations (from 1984 to date)

Reference	Methodology	Literature stream	Engineering process sub-flows [Number – Nature]	Production process sub-flows [Number – Nature]	Engineering and production decoupling configurations [Number – Nature]
Sharman (1984)	Conceptual study	Logistics/ manufacturing strategies	1 – Engineer	4 – Fabricate, Assemble, Deliver, Install	5 – Design and make to order, Make-to-order, Assemble and sell from stock of parts, Sell semi-customized system from stock, Sell from stock
Hoekstra and Romme (1992)	Conceptual study	Logistics/ manufacturing strategies	None	5 – Purchase, Make, Assemble, Ship, Installation	None
Giesberts and van der Tang (1992)	Conceptual study	Information systems	1 – Customer specific, Standard	4 – Drawings, Material components, Semi-finished products, End products	3 – Engineer-to-order, Assemble-to-order, Make-to-stock
Wortmann (1992)	Conceptual study	Information systems	1 – Engineer	2 – Make, Assemble	4 – Engineer-to-order, Make-to-order, Assemble-to-order, Make-to-stock
Hill (1993)	Conceptual study	Logistics/ manufacturing strategies	2 – Design, Changes to standard products	2 – Manufacture, Assembly	5 – Design-to-order, Engineer-to-order, Make-to-order, Assemble-to-order, Make-to-stock
Muntslag (1993)	Single case study research	Information systems	5 – Engineering a specific technology, pre-defined product families, pre-defined product sub-functions and solution principles, pre-defined product modules, pre-defined finished goods	None	Only engineering process is analysed in this study
Lampel and Mintzberg (1996)	Conceptual study	Customisation	1 – Design	3 – Fabrication, Assembly, Distribution	5 – Pure standardisation, Segmented standardisation, Customised standardisation, Tailored customisation, Pure customisation
Amaro et al. (1999)	Multiple case studies research	Engineer-to-order types	4 – produce new design (pure customisation), modification to existing designs (tailored customisation), pick from set of design options (standardised customisation), take existing design (none customisation)	4 – Purchasing, processing, assmbly, delivery	11 non-make to stock configurations (4 engineer-to-order types offering pure customisation; 5 make-to-order types offering tailored or standardised customisation; 2 assemble-to-order types offering standardised or none customisation)

Table 1. (continued)

Reference	Methodology	Literature stream	Engineering process sub-flows [Number – Nature]	Production process sub-flows [Number – Nature]	Engineering and production decoupling configurations [Number – Nature]
Duray et al. (2000)	Survey-based research	Mass customisation	4 – Major revisions, incremental changes to standard designs, combination of a finite set of modules	2 – Make, Assembly, Delivery	4 – Fabricators, Involvers, Modularizers, Assemblers
Winch (2003)	Multiple case studies research	Engineer-to-order types	2 – New design, Major modifications, Configuration of the design	1 - Make	4 – Concept-to-order, Design-to-order, Make-to-order, Make-to-stock
Wikner and Rudberg (2005)	Conceptual study	Mass customisation	2 – New design, design adaptations	2 – Make, Assembly	6 – [ETO_{ED}, MTO_{PD}], [ATO_{ED}, MTO_{PD}], [ATO_{ED}, ATO_{PD}], [ETS_{ED}, MTO_{PD}], [ETS_{ED}, ATO_{PD}], [ETS_{ED}, MTS_{PD}]
Dekkers (2006)	Multiple case studies research	Engineer-to-order types	3 – Integrative engineering, Engineering elements, Manufacturing engineering, Order information transfer to production instruction	5– Materials supply, Parts manufacturing, Assembly, Shipment, Distribution	The order entry matrix is proposed, which combines 4 different OSEPs (order specifications entry point) with 5 different COEPs (customer order entry points)
MacCarthy (2013)	Conceptual study	Customisation	4 – Functional customisation, Superficial customisation, Pre-engineered product variety, Fixed variety	2 – Production, Assembly	5 – Stockists, Builders, Customizers (4 sub-categories), Mass customizers (2 sub-categories), Open systems (4 sub-categories)
Semini et al. (2014)	Single case study	Customisation	5 – Market research & concept design, Basic functional design, Engineering, Major and Minor modifications to existing designs	3 – Procurement, Production, Assembly	2 – Customized design, Standardized design
Willner et al. (2016)	Empirical study: multiple case studies research	Engineer-to-order types	2 – Engineer to precise customer specifications, Major engineering changes, Minor engineering changes, Pre-defined range of options	None	The perspective is always of companies operating make to order and the analysis of this study is on engineering complexity
Gosling et al. (2017)	Empirical study: focus groups and multiple case studies research	Engineer-to-order types	8 – Math research, Science research, Engineering research, Develop codes, Integrate codes, New design, Major modifications, Finalisation	None	Only engineering process is analysed in this study

Table 2. Literature review of key studies related to managerial approaches for decoupling configurations

Key References	Processes addressed	Priority upstream of the CODP	Priority downstream of the CODP	Managerial approaches
Benton and Shin, 1998; Hayes and Wheelwright, 1984; Hoekstra and Romme, 1992; Wemmerlöv, 1984; Wortmann, 1992	Manufacturing management	To assure the availability of materials inventory, in the correct quantities, when the customer order arrives	To assure the availability of the needed capacity (combination of manufacturing lead time and workload of manufacturing resources) after the customer order entry point, to quickly and cost-effectively fulfil a specific order	Make-to-stock: upstream of the CODP just in time (JIT) techniques and/or material requirement planning (MRP) based on standard planning bills
				Assemble-to-order: upstream of the CODP, JIT and/or MRP based on modular planning bills; downstream of the CODP, human resources management, shop floor control, and subcontracting
				Make-to-order: downstream of the CODP human resources management, shop floor control, and subcontracting
				Engineer-to-order: downstream of the CODP project management and risk assessment, reuse of experience, and short communication channels between production and engineering professionals.
Aitken et al., 2002; Christopher, 2000; Christopher and Towill, 2001; Mason-Jones et al., 2000; Naylor et al., 1999	Supply chain management	To assure the availability of materials inventory, in the correct quantities, when the customer order arrives, while assuring reduction of wastes along the supply chain processes, and increasing value creation before the customer order entry point	To assure the availability the needed capacity (combination of supply chain lead times and workload of supply chain resources) after the customer order entry point, to quickly and cost-effectively fulfil a specific order	Make-to-stock: upstream of the CODP lean techniques such as continuous flow manufacturing (Kanban, JIT supply), design for manufacture, set-up reduction, vendor-based integration into the material planning system
				Assemble-to-order: hybrid strategy, mix of upstream (lean) and downstream (agile) approaches. Upstream of the CODP, lean approaches are supported by modular designs; downstream of the CODP agile approaches are supported by reconfigurable manufacturing systems
				Make-to-order: downstream of the CODP, agile techniques such as design for flexibility, re-sequencing production for variety postponement, and vendor managed inventory

Table 2. (continued)

Key References	Processes addressed	Priority upstream of the CODP	Priority downstream of the CODP	Managerial approaches
Chen, 2006; Danese and Romano, 2004; Dekkers, 2006; Rudberg and Wikner, 2004; Salvador et al., 2007; Semini et al., 2014; Veldman and Alblas, 2012; Wikner and Rudberg, 2005	Engineering and production (i.e. procurement, manufacturing and delivery) management	To assure the availability of design repository and materials inventory, in the correct quantities, when the customer order arrives, while assuring reduction of wastes along the engineering and production processes, and increasing value creation before the customer order entry point	To assure the availability of the needed capacity (combination of engineering and production lead times and current load of engineering and production resources) after the customer order entry point, to quickly and cost-effectively fulfil a specific order	Engineer-to-stock and Make-to-stock: upstream of the CODP, lean techniques focused on both engineering and production to manage generic design information and reduce reworks and engineering changes through predefined design standards; concurrent engineering to develop collaborative design and concurrent manufacturability evaluation
				Modify-to-order (major and/or minor changes) and Assembly-to-order: combination of lean and agile through mass customisation (design reuse and adaptation through the organisation of the expertise in a knowledge base), engineering and production integration (concurrent planning, execution and control of sales, engineering and production activities), formal but open engineering change management
				Design-to-order and Make-to-order: agile techniques focused on both mix flexibility and volume flexibility (rapidly change the mix of items and output volumes delivered to the market according to customer requirements with cost-effectiveness), project-based management, and open, ad hoc and informal change management to implement variations coming from evolving insights

Table 3. Case study overview

Company	Approximate Turnover [million €]/ Employees		Sector	Interviewees	Case study: product family (approximate impact on the turnover)
A	75	174	Plastic and rubber machinery	Engineering manager & production dept employees	A1: bender machines (90%)
B	94	114	Plastic and rubber machinery	Engineering manager and production manager	B1: injection moulding machines (70%)
C	44	141	Plastic and rubber machinery	Engineering manager and production manager	C1: extruders (70%)
D	109	181	Plastic and rubber machinery	Engineering manager, senior sales manager & production manager	D1: extruders (80%)
E	247	687	Machine tool	Engineering manager, project manager, sales manager, production manager	E1: laser cutting machines (60%)
F	74	322	Machine tool	Plant manager	F1: machining centres (60%)
G	37	204	Machine tool	Engineering manager and production manager	G1: laser cutting machines (70%)
H	13	52	Machine tool	Plant manager	H1: turning machines (60%)
I	35	104	Machinery for the soap industry	Product manager and sales manager	J1: soap production and confectionery lines (90%)
J	91	275	Machinery for the food industry	Process engineering manager	I1: chocolate production and confectionery lines (70%)
K	200	420	Textile machines	Engineering manager and production manager	K1: winding machines (90%)

Table 4. Case study protocol (data collected)

Source 1: face-to-face interview	
General information	Company's approximate turnover, employees, product portfolio, interviewee/s role
Product family	Description of the main product family provided by the company to the market (more than 60% of the total turnover): product type and main characteristics in terms of customisation (catalogue of standard designs, catalogue of additional customized options, limits in the customisation post-CODP, etc.)
Production decoupling configuration	Referring to the core product family: Number and type of production activities performed to forecast; Number and type of production activities performed to order
Engineering decoupling configuration	Referring to the core product family: Number and type of engineering activities performed to forecast; Number and type of engineering activities performed to order
Managerial approaches	Managerial approaches applied to assure the ability of the company in succeeding the order-promise process (pre and post-CODP approaches to manage and coordinate engineering and production activities); Objectives pursued with the managerial approaches
Performance outcome	Referring to the core product family, assess company's performance, with respect to the market average (0 – not competitive, 1 – low competitive, 2 – on market average, 3 – competitive, 4 – very competitive), related to: (1) flexibility: ability to ensure customisation level required by the customer; (2) price: ability to ensure the price required by the customer while covering expenses; (3) delivery: ability to ensure delivery speed and reliability required by the customer; (4) technology: ability to ensure uniqueness of the technology, designed together with the customer according to specific needs; (5) reliability: ability to ensure low risk for early unexpected defects after sales
Source 2: Direct observations	
Plant tour	Direct observation of the production department during working shifts with the possibility to watch the manufacturing and/or assembly activities and ask additional questions to the employees and/or managers related to the products, the processes, and the managerial approaches
Engineering department tour	Direct observation of the engineering department during working shifts with the possibility to watch the design activities and to ask additional questions to the employees and/or managers related to the products, the processes, and the managerial approaches
Source 3: Official documents	
Company's website	Company info (history, strategy, mission, success factors, etc.); Product info (product types, product features, technical data, applications, etc.)
News and press	Up-to-date info related to e.g. recent business initiatives, new product launches, new technologies introduction
National database	Ten years of history related Italian companies' info: Balance sheet, Number of employees, Sector, etc.
Source 4: Internal documents	
Documents (digital or paper)	Procedures, budgets, product catalogues, etc.
Information systems	Product data management systems, production planning systems

Table 5. Findings of managerial approaches applied by the case studies

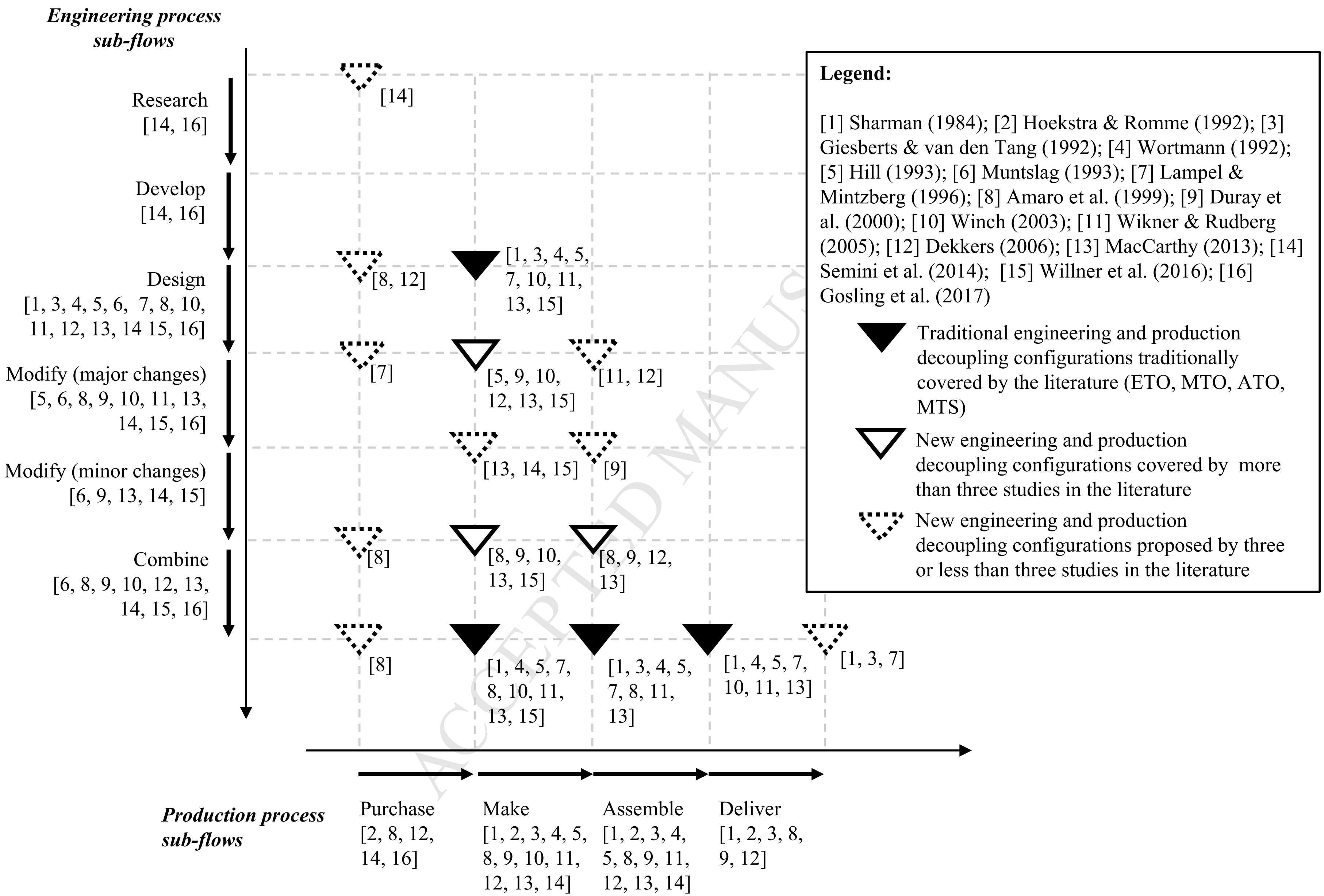
Priority	Managerial approach	Special machines		Customised machines				Standard customised machines			Modular machines	
		C1	**I1**	**E1**	**F1**	**G1**	**H1**	**A1**	**D1**	**K1**	**B1**	**J1**
1. To assure design availability when the customer order arrives	Data management systems: formalisation of requirements with the support of information system (e.g., configurators) to increase the re-use of existing designs and create seamless information flow (Mello et al., 2017, 2015b)	X	X	X	X	X	X	X	X	X	X	X
	Standard-work procedure: adoption of standard working methods and design rules in the engineering process (Dekkers, 2006; Mello et al., 2015a)							X	X	X	X	X
	Modular designs: reduction of engineering efforts through the application of modularity in the product design to exploit component sharing and platform-based systems (Johnsen and Hvam, 2018; Pero et al., 2015; Schoenwitz et al., 2017)			X		X	X		X	X	X	X
2. To assure material availability when the customer order arrives	Special contracts with suppliers: specific agreements made with the suppliers to assure quick availability of materials when needed (Semini et al., 2014; Gosling et al., 2017)			X	X	X	X	X	X	X	X	X
	Lean manufacturing: use of lean practices in the production process to derive better value from processes and sustain performance under uncertainty and complexity (Birkie et al., 2017; Birkie and Trucco, 2016)				X	X				X	X	
	Rolling MRP: hierarchical and incremental work planning of the production activities based on generic forecasts for a specific planning horizon and the dynamic reservation of resources when a specific order is confirmed (Carvalho et al., 2015; Chen, 2006; Rossi et al., 2017)			X			X	X	X			X

Table 5. (continued)

Priority	**Managerial approach**	**Special machines**		**Customised machines**				**Standard customised machines**			**Modular machines**	
		C1	**I1**	**E1**	**F1**	**G1**	**H1**	**A1**	**D1**	**K1**	**B1**	**J1**
3. To assure engineering and production coordination upstream of the customer order entry point	Inter-functional teams: use of coordination teams, composed by people from different functions, to align sales, production and engineering departments to function goals, manage and synchronise their activities (Danese and Romano, 2004; Salvador et al., 2007)	X	X	X	X	X	X	X	X	X	X	X
	Early supplier involvement: early collaboration with the supplier in the design phases to improve the overall project performance, without necessarily the presence of contractually defined partnerships (Mello et al., 2017)			X	X	X	X		X	X	X	X
	Concurrent engineering: use of teams composed by people from different technical backgrounds (e.g., electrical engineering, mechanical engineering, numerical control programming) to jointly develop and implement technical solutions (Mello et al., 2015a)							X	X	X	X	X
4. To assure engineering capacity and capability downstream of the customer order entry point	Workload balancing: planning and control of the engineering process aimed at increasing the visibility on the engineering resources availability and constraints, efficiently assigning and balancing the design tasks, and quickly detecting and solving problems (Hinckeldeyn et al., 2014; Wesz et al., 2018)	X	X	X			X	X	X			
	Engineering knowledge management: formalisation of knowledge, experience and skills to manage process variety (Gosling et al., 2017; Veldman and Alblas, 2012)	X	X		X	X						

Table 5. (continued)

Priority	Managerial approach	Special machines			Customised machines		Standard customised machines			Modular machines		
		C1	**I1**	**E1**	**F1**	**G1**	**H1**	**A1**	**D1**	**K1**	**B1**	**J1**
5. To assure Production capacity and capability downstream of the customer order entry point	Vertical integration: engineering and production processes are considered core competences to leverage on product and process knowledge and increase internal flexibility (Gosling and Naim, 2009; Hicks et al., 2001)			X	X	X	X	X	X			
	Late changes management: formalisation of knowledge, experience and skills of the production department to identify unexpected deviations of the engineering activities (product redesigns) and fix them on site (Mello et al., 2015)	X	X	X			X					
6. To assure engineering and production coordination downstream of the customer order entry point	Project management expertise: definition of procedures and rules to plan project activities and control the project status in terms of both times and costs (Adrodegari et al., 2015)	X		X	X	X	X					
	Daily meetings: to organize periodical meetings to align and update all the functions involved in the project and make quick decisions according to the project status (Cannas et al., 2018a; Wesz et al., 2018)	X	X		X	X						
	Engineering and production overlapping: anticipation of production activities before the end of the engineering ones by sharing incomplete design information, to perform the two processes simultaneously and shorten the lead times (Mello et al., 2015b; Wikner and Rudberg, 2005)	X	X	X		X						


Engineering process sub-flows
Research [14, 16]
Develop [14, 16]
Design [1, 3, 4, 5, 6, 7, 8, 10, 11, 12, 13, 14 15, 16]
Modify (major changes) [5, 6, 8, 9, 10, 11, 13, 14, 15, 16]
Modify (minor changes) [6, 9, 13, 14, 15]
Combine [6, 8, 9, 10, 12, 13, 14, 15, 16]
[14]
[8, 12]
[1, 3, 4, 5, 7, 10, 11, 13, 15]
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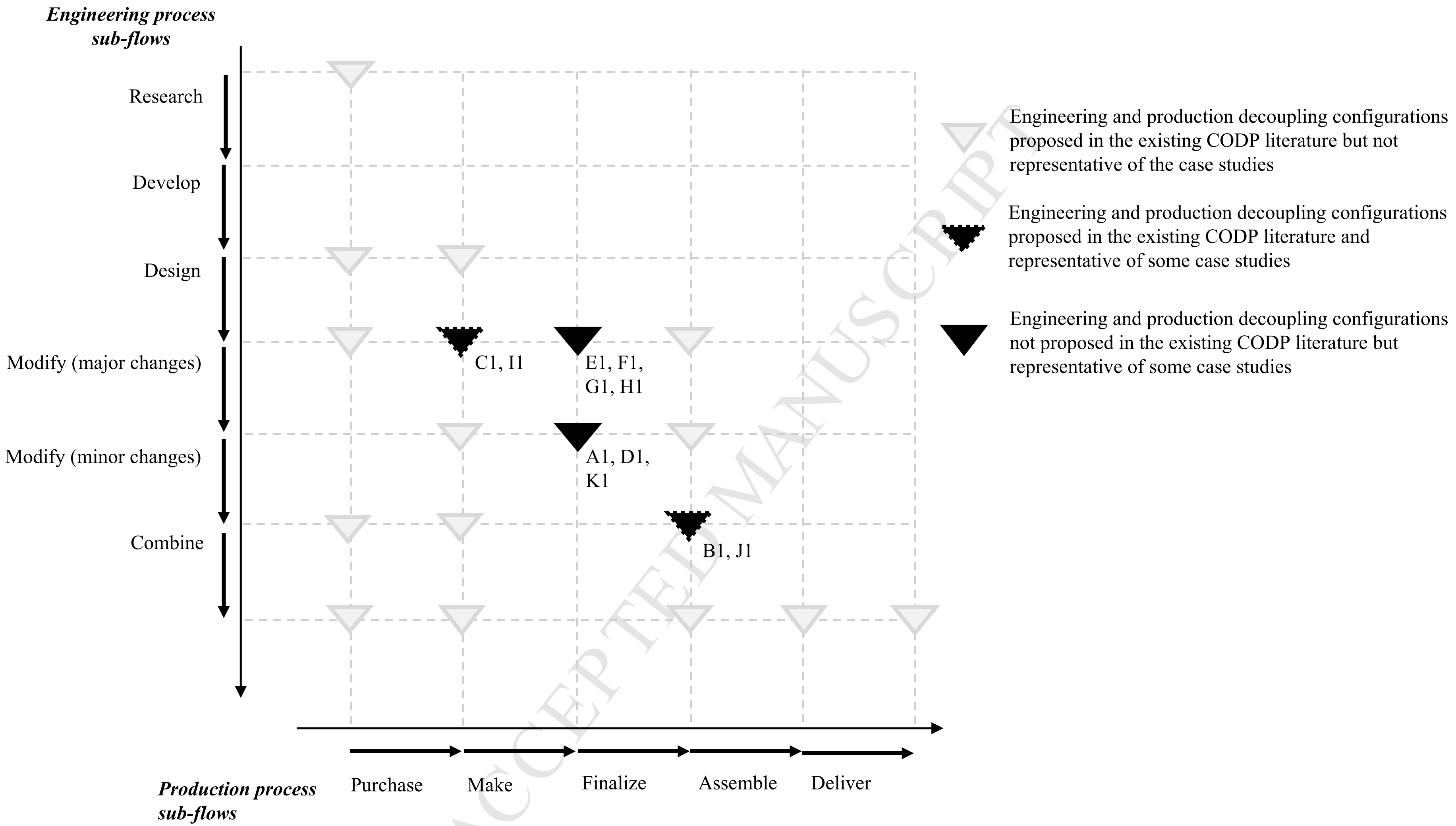
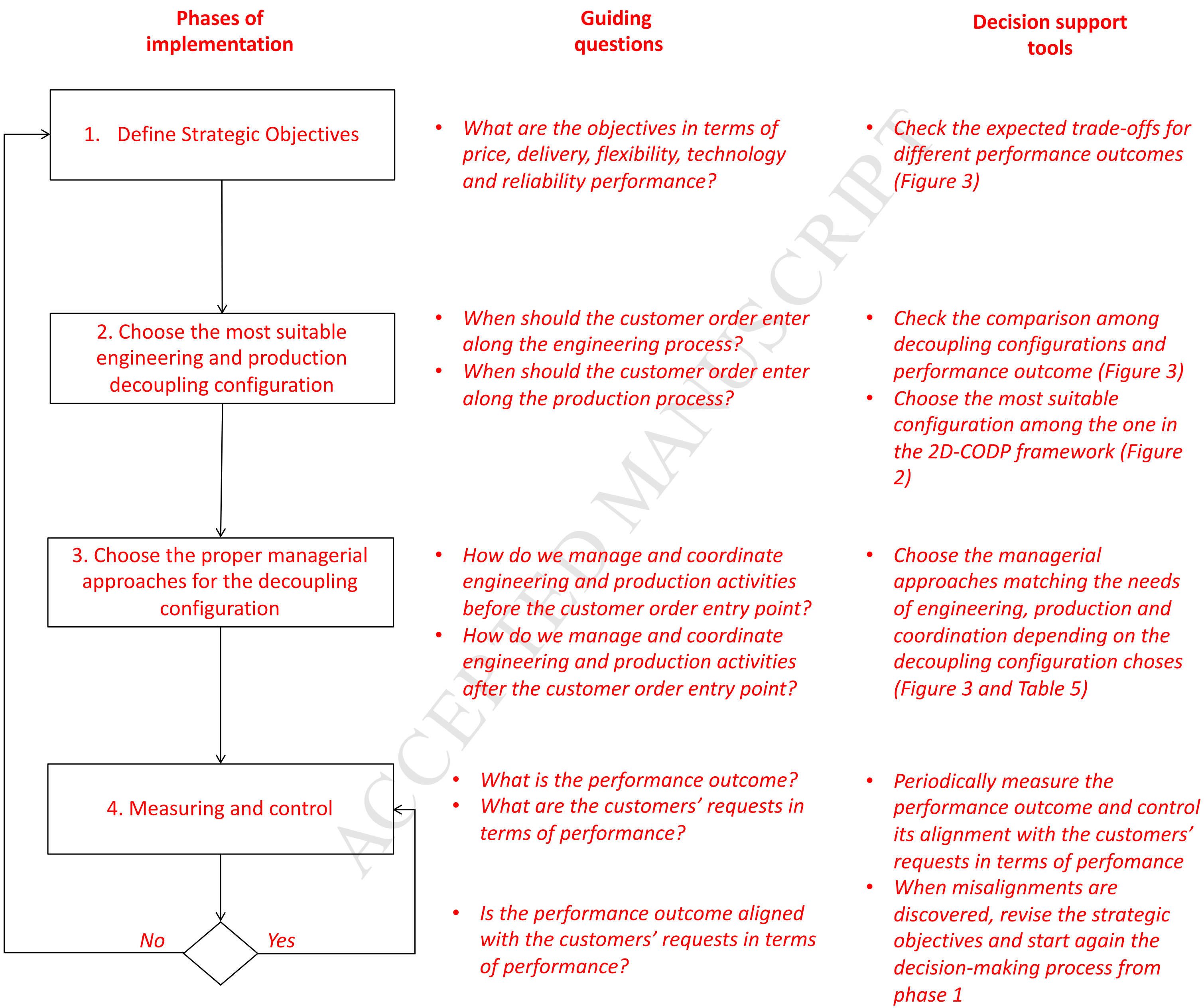
[8, 9, 12, 13]
[8]
[1, 4, 5, 7, 8, 10, 11, 13, 15]
[1, 3, 4, 5, 7, 8, 11, 13]
[1, 4, 5, 7, 10, 11, 13]
[1, 3, 7]
Production process sub-flows
Purchase [2, 8, 12, 14, 16]
Make [1, 2, 3, 4, 5, 8, 9, 10, 11, 12, 13, 14]
Assemble [1, 2, 3, 4, 5, 8, 9, 11, 12, 13, 14]
Deliver [1, 2, 3, 8, 9, 12]
Legend:
[1] Sharman (1984); [2] Hoekstra & Romme (1992); [3] Giesberts & van den Tang (1992); [4] Wortmann (1992); [5] Hill (1993); [6] Muntslag (1993); [7] Lampel & Mintzberg (1996); [8] Amaro et al. (1999); [9] Duray et al. (2000); [10] Winch (2003); [11] Wikner & Rudberg (2005); [12] Dekkers (2006); [13] MacCarthy (2013); [14] Semini et al. (2014); [15] Willner et al. (2016); [16] Gosling et al. (2017)
Traditional engineering and production decoupling configurations traditionally covered by the literature (ETO, MTO, ATO, MTS)
New engineering and production decoupling configurations covered by more than three studies in the literature
New engineering and production decoupling configurations proposed by three or less than three studies in the literature


Engineering process sub-flows
Research
Develop
Design
Modify (major changes)
Modify (minor changes)
Combine
C1, I1
E1, F1, G1, H1
A1, D1, K1
B1, J1
Production process sub-flows
Purchase
Make
Finalize
Assemble
Deliver
Engineering and production decoupling configurations proposed in the existing CODP literature but not representative of the case studies
Engineering and production decoupling configurations proposed in the existing CODP literature and representative of some case studies
Engineering and production decoupling configurations not proposed in the existing CODP literature but representative of some case studies

Engineering and decoupling configurations	Modular machines (B1, J1)	Standard-customised machines (A1, D1, K1)	Customised machines (E1, G1, F1, H1)	Special machines (C1, I1)
Indicative Performance Outcomes	Price ●●●○ Time ●●●○ Flexibility ●○○○ Technology ●○○○ Reliability ●●●○	Price ●●○○ Time ●●○○ Flexibility ●●○○ Technology ●●○○ Reliability ●●○○	Price ●○○○ Time ●○○○ Flexibility ●●●○ Technology ●●●○ Reliability ●○○○	Price ○○○○ Time ○○○○ Flexibility ●●●● Technology ●●●● Reliability ○○○○
Link to Priorities	Focus on Priorities 1, 2 and 3, ensuring co-ordinated design and material availability when the customer order arrives	Focus on Priorities 1, 2 and 3, ensuring co-ordinated design and material availability when the customer order arrives	All priorities relevant, so capability in line with all priorities needed. Hence, balancing co-ordination priorities 3 and 6 and trade-offs are a particular focus.	Focus on Priorities 4, 5 and 6, ensuring engineering and production capacity and co-ordination to meet customer requirement.
Engineering process needs	• Focus on modularization of design elements (Upstream) • Focus on supporting mix and match capability (Downstream)	• Focus on design for easy reconfiguration (Upstream) • Focus on adapting designs through configuration (Downstream)	• Focus on design for manufacture (Upstream) • Focus on capacity management and meeting requirements (Downstream)	• Focus on engineering knowledge management and planning (Upstream) • Focus on capacity management and meeting requirements (Downstream)
Production process needs	• Focus on forecasting expertise for different modules and subassemblies (Upstream) • Build in advance a reliable and efficient supply network (Upstream) • Assure capability to integrate modules (Downstream)	• Focus on good forecast-based materials planning (Upstream) • Build in advance a reliable and efficient supply network (Upstream) • Assure responsiveness of production reacting to dynamic variety of a single customer order (Downstream)	• Build in advance a reliable and efficient supply network (Upstream) • Focus on control of production activities (Downstream)	• Build relationships with suppliers who can support 'specials' (Upstream) • Focus on flexibility and responsiveness, such as procedures for managing changes (Downstream)
Coordination needs	• Focus on optimising the modular system in co-ordination activities. • Involve external stakeholders in the development of product architecture • Involve all departments in the detail design	• Focus on forecasting trends for anticipating possible configurations in co-ordination activities • Involve external stakeholders in the development of product architecture	• Focus on balancing and minimising upstream and downstream trade-offs • This will require expertise on co-ordination upstream (e.g. early supplier involvement) and downstream (e.g. Project management), as well as concurrent activities	• Focus on realising unique designs and technology development as co-ordination challenge • Involve all departments in R&D • Consider performing engineering and production activities concurrently


Phases of implementation
Guiding questions
Decision support tools
1. Define Strategic Objectives
• What are the objectives in terms of price, delivery, flexibility, technology and reliability performance?
• Check the expected trade-offs for different performance outcomes (Figure 3)
2. Choose the most suitable engineering and production decoupling configuration
• When should the customer order enter along the engineering process?
• When should the customer order enter along the production process?
• Check the comparison among decoupling configurations and performance outcome (Figure 3)
• Choose the most suitable configuration among the one in the 2D-CODP framework (Figure 2)
3. Choose the proper managerial approaches for the decoupling configuration
• How do we manage and coordinate engineering and production activities before the customer order entry point?
• How do we manage and coordinate engineering and production activities after the customer order entry point?
• Choose the managerial approaches matching the needs of engineering, production and coordination depending on the decoupling configuration choses (Figure 3 and Table 5)
4. Measuring and control
• What is the performance outcome?
• What are the customers' requests in terms of performance?
• Is the performance outcome aligned with the customers' requests in terms of performance?
• Periodically measure the performance outcome and control its alignment with the customers' requests in terms of perfomance
• When misalignments are discovered, revise the strategic objectives and start again the decision-making process from phase 1
No
Yes