Modularity and operational efficiency in engineer to order companies: a study in the machine tool industry

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Abstract: Engineer-to-order (ETO) firms design and manufacture products according to customers' orders. As such, they induce a high level of variety in production, which makes the management of their operations particularly complex. This complexity, coupled with increasing competitive pressure, led many ETO firms to leverage product modularity to improve their operational efficiency. Extant literature on the impact of modularity on operational performance in ETO firms is mainly focused on construction and neglects other relevant sectors. Existing studies, however, point to a potentially positive impact of modularity on products and processes in ETO. First, although ETO companies using modularity create lower variety, they are more efficient than ETO companies that provide fully tailor-made solutions. Second, modular design may decrease the risk of misunderstanding customers' needs, thus preventing reworks. Third, the reuse of designs among many customer orders can reduce engineering lead times and their variability. Fourth, modularity makes production activities more decoupled and allows task parallelization. Finally, modularity can improve scale economies in purchasing and production. In this paper, we choose an exploratory, inductive approach, and focus on ETO machine tools production, a highly relevant sector for the Italian economy. In particular, we deal with the question: how can modularity impact the operational performance of ETO machine tool producers? To answer this question, we conduct expert interviews in seven ETO machinery companies in Northern Italy. We integrate the key insights from the interviews into a causal map that illustrates how ETO machine tool producers can leverage modularity to improve their operational performance, in particular their delivery times. We also highlight the importance of our research for practitioners and for academics.

Keywords: Engineer to Order; Machine Tool; Machinery; Modularity

1. Introduction

Engineer to Order (ETO) is an order fulfilment strategy, in which products are designed and produced according to customers' specifications (Wortmann, 1992). Several industrial contexts such as shipbuilding, construction and machinery adopt ETO to respond to customers' demand (Cigolini *et al.*, 2020). Despite their differences, these industries commonly offer high product variety due to the customization level allowed by the ETO paradigm.

Over the last years, however, ETO companies are facing fierce price competition and are required to squeeze their costs. This is due to increasing globalization, changing market dynamics, shorter product lifecycles (Cannas *et al.*, 2020), and the advent of new technologies (Patrucco et al., 2020). Therefore, ETO companies need to increase their operational efficiency to survive without compromising product variety, a major distinguishing factor from other contexts.

Product modularity is a design concept that can support ETO companies in overcoming the trade-off between variety and operational performance (Salvador, Forza and Rungtusanatham, 2002). Recent studies have suggested that this may also hold true for ETO companies. For instance, Cannas *et al.* (2019) argue that product modularity is a tool for ensuring design availability before the arrival of customers' orders. Engineering efforts are reduced due to component sharing and platform-based systems. Later, Cannas *et al.* (2020) found design modularity among the best practices ETO companies use to overcome the pre-implementation challenges of product configurators, which are software systems that can support firms in the shift towards mass customization.

To the best of our knowledge, studies discussing the relationship between product modularity and operational performance in ETO companies are still scarce. In particular, the adoption of modularity in the machinery industry is still understudied. Hence, the following research question *(RQ): how can modularity impact the operational performance of ETO machine tool producers?*

This paper is organized as follows. Section 2 deals with the theoretical background. Section 3 describes the research methodology. Section 4 presents the research results, while Section 5 integrates them into a theoretical framework. Finally, Section 6 summarizes the main insights of the work, shows its major limitations, and outlines possible directions for future research.

2. Theoretical Background

This section provides a narrative literature review on ETO and the impact of modularity in the ETO context.

2.1 Engineer to Order

Despite its importance, ETO has been neglected by researchers for many years, with the first systematic literature review published only in 2009 by Gosling and

Naim (2009). The definition of ETO has evolved during the past decades. The concept of ETO is strictly related to the Customer Order Decoupling Point (CODP). "The CODP refers to the point in the material flow from where customer-order driven activities take place; stated differently, the activities upstream of the CODP are driven by planning activities based on forecasts, rather than on firm customer orders" (Wortmann, 1992, p.80). ETO companies have a CODP located at the engineering stage, in other words all the activities ranging from engineering to delivery are conducted according to a specific customer request. For instance, Wortmann (1992) classifies aircrafts as typical ETO products and machine tools as Make to Order (MTO) products.

Nevertheless, Wortmann's definition has some weaknesses. For example, it ignores that the engineering stage—analogously to the supply chain—consists of many phases. Therefore, scholars have proposed new frameworks that combine both chains together (e.g. Amaro, Hendry and Kingsman, 1999). A recent framework has been built upon the two-dimensional CODP (2D-CODP) matrix after the analysis of several case studies from the Italian machinery industry (Cannas *et al.*, 2019). This matrix allows the distinction among different "shades" of ETO products: special machines, customized machines, standard customized machines, and modular machines (*ibidem*). Cannas *et al.* (2019) and Cannas *et al.* (2020) widely discuss the relationships between the different positions of the 2D-CODP and the managerial practices adopted by ETO companies. In these studies, modularity has been argued as a relevant practice adopted by ETO companies, a detailed analysis of its impact on the operational performance is still missing.

2.2 Modularity

"In spite of its age, modularity is a splintered concept" (Starr, 2010), and there is no unique definition that captures all its facets. Many specific definitions of modularity that are applicable to different ETO industries have been proposed. For instance, Gosling et al. (2016) proposed a definition for the construction industry. However, there is no definitions of modularity that could work for *every* ETO industry. Therefore, in this paper, we stick to a general-purpose definition: "product modularity is the use of standardized and interchangeable components or units that enable the configuration of a wide variety of end products" (Jacobs et al., 2007).

2.3 Modularity in ETO Contexts

The application of modularity in product design has impacts on the performance of the engineering and production processes of ETO companies, and in turn on the planning of the production.

Regarding the engineering process, literature suggests that high modularity can be detrimental for the design flexibility of ETO companies. In construction and shipbuilding industries, Pero et al. (2015) observed that higher product modularity increases the levels of prefabrication and reduce the opportunity for the customer to ask for late changes in product development.

However, this high rigidity has a positive impact on production planning, since high product modularity improves design accuracy at the early stages of the order fulfilment. This happens for two main reasons. First, modularity helps the translation of specifications into well-defined solutions, as it provides customers with familiar features to select from, and consequently reduces the risk of misunderstanding the customers' needs. This was shown by Hicks et al. (2000) by means of multiple case studies conducted with diverse capital equipment producers. Second, modularity drives the reuse of already existing designs, thus making the engineering process more standard and more accurate, as the study by Simpson *et al.* (2014) in a bas valve production company showed.

Modularity also allows for the overlapping of production activities (e.g. Persson and Åhlström, 2006). In addition, the anticipation of production activities before the end of engineering activities by sharing incomplete design information, allows one to perform both processes simultaneously and to shorten the project lead time(Cannas *et al.* 2019).

Modularity has a significant impact on production planning., since it shortens production lead times (parallel execution) and decreases their variability. This has two main consequences. First, activities are less interwoven, thus decreasing complexity on the shop floor. Second, the required level of coordination among the actors involved in the process decreases (e.g. Ulrich, 1995). Whereas a lower complexity has a positive impact on the planning performance due to lower lead time variability, lower levels of coordination may be dangerous for the outcome of the project as well as the planning process. ETO construction companies overcome this trade-off thanks to a careful design of interfaces, which minimize the need to spend time in coordination activities (Pero et al., 2015). Although modularity increases the effort required during the design phase, the higher efficiency achieved in production more than offsets this negative effect (*ibidem*).

3. Methodology

To answer the research question, we performed expert interviews, since they can "outline interrelations in the empirical data […] to develop theoretical approaches" (Döringer, 2020, p.3) and allow "inductive theory development based on empirical data" (*ibidem*).

We focus on small-and-medium enterprises (SMEs) in the machine tool industry because of the scarcity of studies in this sector and because of its importance for the Italian and European economy. To identify SMEs, we analysed the AIDA database (aida.bvdinfo.com), by restricting the results according to the machinery sector – AIDA categories 284 and 289 – and the number of employees – less than 250 people, accordingly to the European definition of SME (ec.europa.eu).

Among the companies we contacted only seven machine tool manufacturers from Northern Italy accepted to participate in the study. Table 1 provides some key data on the companies involved.

We interviewed the Chief Operation Officer (COO) of each company, except for case 2, in which we interviewed the Chief Executive Officer (CEO). Each interview followed the same protocol, which allowed us to stick to the same topics, although the questions were not exactly identical. We adopted a semi-structured approach to let the interviewees speak freely on each topic and to collect as many insights as possible. All interviews were recorded and transcribed, thus gathering a good amount of qualitative data, which was analysed by means of content analysis.

Table 1: key data about the interviewed companies
Source: AIDA, data at 31/12/2018

#	Location	Revenues [M€]	Profit [M€]	Employees	Main Products
1	Alessandria	36.5	0.5	140	Turning and milling machines
2	Biella	17.8	2.5	100	Industrial dosing systems
3	Modena	81.5	7.7	250	Machining centres
4	Verona	29.5	0.3	110	Systems for processing construction materials
5	Treviso	35.0	1.7	150	Metal sheets cutting machines
6	Como	49.0	0.7	90	Recycling systems
7	Imola	100.0	N/A	250	Roller coating machines

The unit of analysis was the product family with the highest impact on the company's turnover. Cases 2,3,5,6, and 7 had one core product family and a few other minor ones, which were neglected. Conversely, cases 1 and 4 had two main product families with very different characteristics, so we treated them separately.

4. Results

In this section, we describe the main results of the interview study. We start by positioning the companies in the 2D-CODP framework, and then analyse the main areas impacted by modularity: engineering, production, product, and supply chain planning.

4.1 Cases' Position in the 2D-CODP Framework

As Figure 1 shows, the companies interviewed occupy different positions on the 2D-CODP-matrix. There are two companies that mainly offer special or customised machines. All other cases, however, rather use a Make to Order fullfillment strategy.

When asked to describe its engineering process, company 5 stated: "the activities on forecast are zero; our engineering process starts only after the order arrives – we are pure ETO". This statement indicates that the decoupling point is placed at the very beginning of the design chain. Concerning production, company 5 mentioned: "we move only on order; we perform 100% of the activities after the order arrives, since the products are unique – we cannot anticipate anything". This suggests that the decoupling point must be at the very beginning of the supply chain.

Case 4a is totally different. "We built the product as a Lego, creating standard elements for the parts of the system, which best suit to be reused in different products." This indicates that the engineering decoupling point is at the "combine" stage. Concerning production, the statement "when the customer order arrives, we have everything ready, and we have only to assemble it" suggests that the CODP should be between finalization and assembly.

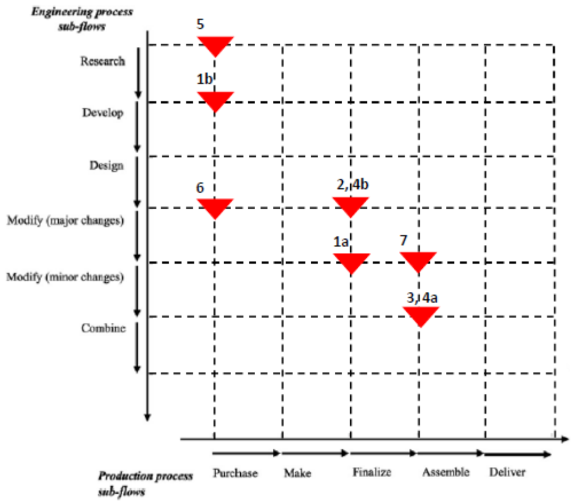

Figure 1: Cases' Positioning on the 2D-CODP Matrix

4.2 Modularity & Engineering Process

Modularity increases the level of standardization in the design process, typically with a positive impact on the operational performance. First, it benefits the speed of operations. Company 7 stated, "standard components could skip the design phases and go directly in production, reducing the total production lead times". Second, it improves design reliability. Company 6 mentioned, "the more I am able to standardise, the better I translate the requirements, and the fewer errors I incur. The more I introduce novelty and new elements, the higher is the number of errors". Both advantages are due to the possibility of reusing already existing solutions. For the company in case 4, "modularity brings enormous benefits, especially in design, since the engineers can reuse such modules without developing them from scratch."

The achievements of these benefits is not trivial. Some interviewed experts point to the fact that modularity has a negative impact on the efficiency of the initial stages of the engineering process, which should be offset by a higher efficiency in the last stages. As it is pointed out in case 1, "if you have a modular product, in the initial phases it is more likely that the client would ask for changes".

The efficient management of these changes is key, as company 4 stated: "In our industry, we do not start the project, if we do not have a well-defined and signed layout. So, late changes, if accepted, imply that the project stops, so that we validate the requests and then restart", leading to "delays" and "additional costs".

Modularity supports companies in handling the changing requests that customers may come with after having placed their orders. As mentioned by company 4, "The more a product is modular, the lower the changes impact on its feasibility". Company 2 elaborates more on the changing requirements by customers. "Modularity simplifies the management of such requests of changes: if the requests are limited only to the modular component, then it is perfect. You adopt modularity exactly for this reason. The main goal is to achieve a product made as a "Lego", reducing at minimum the number of activities to be performed on order". Similarly, company 5 claimed: "If the modules are already available, this simplifies the management of late changes. However, it should be standard: if the customer asks for customizations, this is not true. At the same time, modularity allows limiting the impact on the single module".

Company 6, which is positioned in the top left corner of the 2D-CODP-Matrix, summarizes well the benefits of modularity, as they were asked, whether modularity is advantageous: "yes and no, in the sense that it depends on the market you are in. In our case, the degree of customization is high, thus the modularity we adopt cannot be applied in a standardised manner. In particular, the design process is very difficult to be standardized: the layout is continuously changing".

4.3 Modularity & Production Process

The main impacts of modularity on the production dimension are twofold. First, it increases the standardization level of activities, making them easier and faster to perform. Second, it allows decoupling, and consequently, parallelises activities, with benefits both on delivery speed and delivery reliability.

The standardization of activities mainly increases the efficiency of human resources, since "you can formalize the activities and repeat them" (case 5), so that "it is not necessary to train the workforce to show how to manage activities and products, which do not differ from the usual ones" (case 1). In other words, modularity favours learning economies in the production process and improves productivity.

The impact of parallelization is explained by company 3: "modularity allows the parallelization and higher independence of the activities in production and assembly. For example, let us think about a machine composed of three units: modularity allows creating interconnections between the units, which are independent from what the module itself does. In this case, the production process is independent, and I can go in parallel and produce simultaneously". The activities' parallelization allows for a better workload balancing. In company 3, "modularity creates standard interconnections, and reduces the variables to be controlled, easing the process of workload balance". This means a better capacity utilization, by "levelling the demand peaks", "since modularity allows preassembling some groups when there is a slowdown in sales" (case 1). Consequently, modularity also improves the company's on-time delivery and order completion. "A modular product allows solving such problems (i.e. delays in the project), since I can work in parallel and potentially make up for the lost time by reallocating the resources. Thus, modularity makes more flexible and precise in defining and respecting the deliveries" (Company 5).

To conclude, the higher the level of modularity, the greater the benefits in production, but this may not be possible to achieve, if degree of customization is high. Therefore, company 5 sees that "having everything modularised and standardized allows simplifying a lot of processes. In our case, this is not true: we have processes that are different, thus it is not possible to know in advance what you will have to do".

4.4 Modularity & Product Innovation

Table 2 summarizes the answers of the interviewees with respect to product innovation. In three cases, modularity has a positive influence on innovation. In five cases it has no impact, and in one case, modularity is even seen a barrier. The positioning of the cases on the 2D-CODP matrix provides an explanation. Companies 3, 4, and 6, which have a highly modularity in the engineering process, saw modularity as an enabler of innovation, while case 5, with the lowest modularity, saw it as a barrier.

According to case 5, modularity could jeopardise innovation, since "it could limit the freedom of thought of the engineers and technical department". This concern is, in part, shared also by the other companies. For instance, case 2 stated that "it is fundamental to manage the trade-off when adopting modularity: even if it does not limit the process of innovation, for sure modularity makes it harder."

Other companies, however, could overcome this issue by relying on the skills of their engineers who should be able to understand when to "recycle" a module and when to design and develop a new one. As case 4 stated: "modularity is not absolutely a limit for the process of innovation: everything is in the skills of the technical office, which should not be blind in adopting modularity. A skilled engineer is able to look forward and create a flexible product that suits market and clients' needs". This is in line with case 3, which sees that "the key stands in the engineering department … [because it] should catch everything done in the past, and then recognise how (and whether) to adopt it".

Indeed, if properly managed, modularity fosters innovation. Modular designs lead to the management of higher volumes which, in turn, justify higher investments in innovating them, eventually by creating "excellence centres". This is what case 3 stated: "the creation of excellence centres allows the specialization, increases the concentration of people, the process becomes standard, efficiency increases, as well as quality. Similar products allow and improve the number of investments, increasing again efficiency and reliability. If quality and reliability increase, volumes increase too. If volumes increase, you can increase the number of investments, and therefore make standardisation at higher degrees”.

Case	Modularity limits innovation	Modularity does not limit innovation	Modularity fosters innovation
1a		X	
1b		X	
2		X	
3			X
4a		X	
4b			X
5	X		
6		X	
7			X

Table 2: Impact of modularity on product innovation

4.5 Modularity & Supply Chain Planning

Modularity induces a higher level of standardization in production activities. “Everything modular, standard, repetitive brings benefits at 360 degrees in the whole company. Thanks to the modularity, the standardisation, and the repetitiveness introduced, it is easier to estimate the lead time of the activities, therefore, to make reliable planning” (company 4). This standardization is strictly related to a lower complexity of products and processes. As another mass customizer company, case 3notes “the management becomes very difficult, if you have lots of variables to control; modularity, instead, means less variable to control. Therefore, it allows to plan and control better the activities. There are lower variability and fewer external variables”.

On top of these “internal” factors, some benefits from the “external” side are worth mentioning, as “it is different to plan the procurement of ten pieces or one hundred pieces” as argued by company 3. “Indeed, if you have standard and common components, you have more power with the supplier because you buy higher volumes, […] so that the procurement is managed with recall orders, with reduced and more stable lead times” (case 1). In this sense, it is interesting to notice that companies 3 and 4 even managed to implement lean procurement practices, e.g. by using Kanban systems. “Having modular products allows to apply lean principles”, stated company 3, because of the higher standardization that modularity brings to all the parts of the company.

Companies 5 and 6, which adopt lower levels of modularity, mentioned fewer benefits also from the planning perspective. For instance, company 5 said: “with a standard product, the planning process would not be completely linear, but for sure easier. In our case, we have two huge variables: the specific request at the machine level, and at the material (to be processed) level. These two factors create huge uncertainty. We have to build unique systems Therefore, it is difficult to make reliable and precise estimates. Without historical data, it is impossible to make good forecasts. In our case, modularity does not help in solving such uncertainty. These two variables are too big to be controlled. Modularity allows only to reduce the lead time variability for the components less customised”. Company 6 also stresses this point: “Modularity does not help in improving the ability to forecast activities’ lead times, since they are mainly determined by the most customised and complex elements. The module itself does not matter. We can have small modules but composed by really customised and complex elements”.

5. Discussion

We summarise the results of our interview study in a causal map (Figure 2). Concerning the operational performance, we consider five dimensions: cost, speed, dependability, quality and flexibility (Slack, Brandon-Jones and Johnston, 2013). However, the impact of modularity on the latter did not emerge from interviews, which is why it does not appear in our framework.

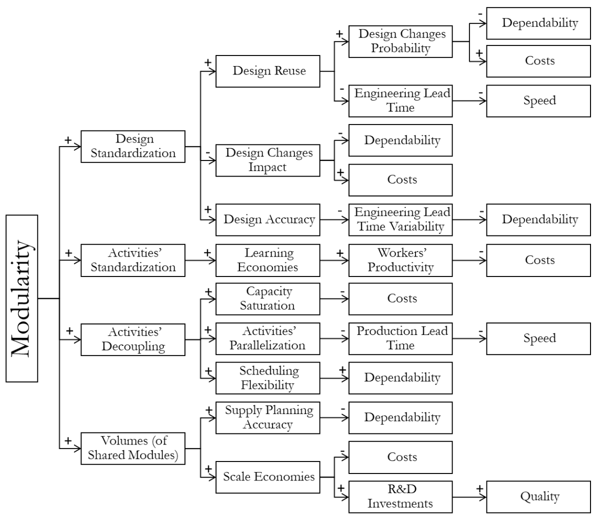

Figure 2: Modularity & Operational Performance Causal Map

The causal map consists of different variables relevant for an ETO company such as scheduling flexibility and production lead time. These variables are connected by arrows, which represent a logical link. Each arrow ends with a sign, either positive or negative, which is determined by the relationship between the two variables connected by it, with the following convention: if the first variable increases and the second variable increases, then the sign is positive; instead, if the first variable increases and the second variable decreases, the sign is negative.

The analysis of the causal map reveals that modularity brings about several benefits to the operational performance of ETO machine tool producers. First, it reduces costs, thanks to a lower effort required to react to late design changes, a higher workers’ productivity, a better level of capacity utilization, and higher scale economies in the procurement of raw materials and sub-components. Second, it improves speed thanks to shorter engineering and production lead times. Furthermore, it increases the delivery dependability thanks to a lower time required to react to late design changes, a lower variability of engineering lead times, a higher scheduling flexibility, and a higher supply planning accuracy. Finally, it improves quality thanks to the higher research and development investments in the "excellence centres" specialized in the different modules.

However, modularity has some drawbacks. It can lead to higher probability of design changes, especially in the early stages. This is due to the requirement to adjust modules to properly meet customers' requests in ETO contexts. In certain markets, these design changes are so frequent and cause high costs and delays that may offset all other benefits. Therefore, to serve these markets, a company should position its 2D-CODP at earlier stages of engineering and production, which is related to less modular products. For the companies located in the bottom-left corner of the 2D-CODP matrix, modularity could be highly beneficial.

6. Conclusions

This paper investigates, through an interview study-based research, the implications of modularity on operational performance – especially cost, speed, dependability, and quality – in ETO companies in the Italian machinery industry. From the perspective of operations, modularity increases speed and quality.

A trade-off exists between dependability and costs. On the one hand, design standardization has a negative impact on dependability, because of the higher design change probability. On the other, this effect is mitigated by the positive impact of the lower impact of design changes and the higher design accuracy. A similar effect is observed for costs, since design change probability increases costs, while lower design change impact improves efficiency. So, design changes determine the global impact on dependability and costs. The probability that a customer requires a change, as suggested by Cannas et al. (2020), depends on the type of customer, and on the positioning of the company product line in the 2D-CODP matrix.

This paper extends the discussion on the role of modularity in manufacturing companies by studying the implications of modularity in a traditional ETO sector, where modularity has been under-investigated: the machine tool industry. The results support Cannas et al. (2019) in showing that modularity is a design strategy applied with a different intensity in the machinery industry. We extend their observation by highlighting the implications on performance of the choice of pursuing a modular design.

This paper can support managers in assessing the impact of pursuing modularity on the operational performance. Figure 1 can be used as basis for a discussion between engineering and production departments, since it allows to see on a single chart the impacts of a design decision (modularity) on production processes.

This research exhibits, however, some limitations, due to the limited sample and the fact that the data collected are qualitative, thus not allowing to quantify the impact. Future research could be devoted to extending the sample by conducting further interviews or to test the relationships identified by means of a large-scale survey. Furthermore, other benefits related to modularity could be explored more deeply. For instance, the relationship between modularity and lean management, which was cited by companies 3 and 4, could deserve more attention in the future.

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