Materials management and cost reporting in "engineer to order" environments: a comprehensive review of research trends and practices

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Abstract: Engineer-to-order (ETO) manufacturing systems realize highly customized products based on customer requirements. Such products, in most cases results of unique projects, rarely present a complete Bill of Materials (BoM) that can easily support the supply and management of raw materials and semi-finished products. Still today the high variability in products for ETO, above all for enterprises not very structured such as small or medium ones, makes it complex to efficiently manage the physical and information materials flows and consequently to correctly report the costs sustained for a single project. The absence of materials control can imply shortages of materials or in the worst case an increase in the quantity of materials bought that could become unusable after a pre-defined period. Furthermore, the lack of control on materials costs, above all in the difficult actual historical period characterized by pandemics and disruptions of any type, can hide the real obtained profit. To provide a comprehensive state-of-the-art on this topic, this research study, methodologically based on a scoping literature review, aims to identify the main trends in the material management and cost monitoring systems for ETO environments developed during the last 20 years focusing on the different functions involved in material-related processes. Moreover, the analysis allowed us to identify the main gaps in this research field. The findings reveal an absence of frameworks and models that include all the business functions (sales, engineering, buyers, etc.) involved in single project management. Only one or two of them are deeply analysed in the literature, and their processes are investigated and improved singularly rather than looking at the entire flow of materials from the request to the use of the materials. Moreover, the literature lacks cost-monitoring approaches for supporting companies in material flow monitoring and cost-reporting activities that can be adapted to ETO needs.

Keywords: Materials Management, Decision-making, Cost Monitoring, Engineer-to-Order, Informative Systems

1. Background and motivation

The companies operating in the Engineer-To-Order (ETO) sector provide highly configurable and unique products to meet the particular needs of customers while facing highly competitive pressure and increasingly short lead times. Each order can be considered a real "complex project" that overlaps multiple activities and involves the customer from the early stage of design (Bakås et al., 2023).

The product design phase can begin only after receiving a specific request from the customer, so the Customer Order Decoupling Point (CODP), which is the stock holding point that separates the part of the supply chain that responds directly to the customer from that uses the previsional planning, is positioned upstream of the design phase (Strandhagen et al., 2019). During this phase, the price of the product must be defined according to the customer's specific functional requirements, which must be met exactly. Given the lack of information at this stage (Wehlin et al., 2021), the task of estimating costs is inherently complex: overestimating costs can lead to customer dissatisfaction and lost orders, and underestimating costs can lead to lost profits (Elgh, 2012; Hooshmand et al., 2016). The high complexity of ETO systems can be translated also into the need to coordinate both physical and information flows to ensure the correct functioning of the company (Strandhagen et al., 2019). One of the most important challenges in the ETO sector is being able to track both flows to ensure coordination and traceability within the industrial plant. Traceability offers companies the ability to collect information on all the components of a product, the operations done for procurement, internal movements, the suppliers involved, and the operators employed. This affects product management, the ability to comply with legislation in terms of documentation, while providing after-sales services to the customer, maintenance, and spare parts (Elgh, 2014). Currently, the flow of materials is very irregular and disrupted, so there is a need for an efficient materials management system to ensure the presence of the right quantities at the right time to maintain customer satisfaction (Sjøbakk et al., 2014). In addition, since there are no standardized production processes, the complexity of the information flow between all parties involved in the project is very high (Reid et al., 2019). It is necessary to ensure that information flows properly through the company's areas: beyond external communications, which have an impact on the company's visibility, customer relations, and customer loyalty, internal communications have an equally strategic value that should not be underestimated, although with less obvious immediate impacts. ETO systems require adequate information sharing for the efficient control of manufacturing activities and, at the same time, in the opposite direction, for the progress reporting from the production floor (Strandhagen et al., 2019).

To the best of the authors' knowledge, a review of the most recent scientific studies on the topic of materials management for ETO environments and its contribution to the overall project cost is not present in the literature. Until now, researchers focused on ETO problems and challenges, mainly from the planning point of view (Cannas & Gosling, 2021; Fortes et al., 2023), whereas, regarding the material management, they mainly draw attention to the digitalization needed in logistics tasks (Strandhagen et al., 2019) have been found. Materials, and in general all outsourcing activities, significantly affect the overall cost of a project in ETO environments and even though most of the purchasing tasks are strictly connected to a single project, it is not easy to calculate the related cost easily and comfortably. The relationship between materials management and the correct cost allocation has been not addressed until now. For this reason, this research study, methodologically based on a scoping literature review, aims to identify the main trends in the material management for ETO environments developed during the last 20 years focusing on the different functions involved in material-related processes, the traceability and correct definition of flows and their related costs.

The remainder of this paper is organized as follows. Section 2 describes the research methodology whereas Section 3 presents the main results of the carried-out analyses. Finally, section 4 provides the main discussions and section 5 presents the main conclusions of the study.

2. Research methodology

Scoping reviews summarise complex and heterogeneous topics, which are difficult to evaluate through a precise systematic review of the evidence to identify research gaps and set the scene for a future research agenda (Di Pasquale et al., 2020). This study, methodologically based on a scoping literature review, examined the literature to address the following Research Questions (RQs):

RQ1: What are the business processes and functions involved in the material management for the ETO environment?

RQ2: What are the methods used for materials cost monitoring and or/budgeting in ETO contexts?

RQ3: What are the existing trends and gaps in the ETO material flow management and related cost reporting?

To answer the RQs, a research activity has been carried out in four consecutive steps: (i) the definition of keywords; (ii) the literature database search under constraint; (iii) paper selection according to screening criteria, and (iv) analysis of selected papers, and data extraction.

First, three groups of keywords, reported in Table 1, were defined according to the aim of the study: the first group was related to the type of production system, the second one to the main topic of the search, and the last one to the type of sector. All possible combinations of these keywords were searched in the Scopus database in October 2023. The search string, which covered the titles, keywords, and abstracts of the papers, was constructed by combining the three macro-groups of interest through a conjunction operation (boolean operator 'AND'), while the keywords were inserted as a disjunctive combination of elements (boolean operator 'OR'). The search was limited to papers written in English in the last 20 years (2003-2023), and whose document type was conference proceedings, articles, or review.

Table 1: Research keywords

Group 1	Group 2	Group 3
Engineer* to order, Engineer*-to-order	Material*, Inventory, Logistic*, Supply*	Manufactur*, Industr*, Product*

The next screening was divided into two steps. The first one consisted of reading titles and abstracts to exclude all papers that were not related to the main topics of the search; the second step, instead, by reading the full text, enabled the identification of the most relevant papers. Specific inclusion/exclusion criteria were defined to carry out both of the two screening phases. All papers that present the material flow management models, frameworks that illustrate the ETO production processes to enable traceability and visibility of the entire supply chain, or methods to solve problems of specific industrial processes were included. Instead, papers not related to the manufacturing environment such as the construction or papers in which materials and costs were not the focus were excluded. After the screening process, the selected papers were deeply analysed and the most relevant information was collected in an Excel file such as:

- Type of innovative contribution (empirical analysis, case studies, frameworks, and developments of new models/software)
- Proposed/developed tool or methodology
- Industrial sector in which methods, models, or software were implemented.
- Industrial processes involved in the specific case study such as sales engineering, product design, production planning, procurement, production, closing, and reporting.
- Business functions involved in the processes such as buyers, sales, engineers, etc.
- Methods developed (or simply used) for materials cost monitoring and budgeting.

3. Findings

The carried-out search led to the generation of a database of 169 papers, which, following the application of filters such as time horizon, were reduced to 151. At the end of the first screening phase, based on the analysis of the title and abstract, only 46 papers moved on to the next phase and were analysed in full text to get a better understanding of the contents useful for the final evaluation. In the end, only 12 papers matched the inclusion criteria mentioned in Section 2 and their analysis findings have been reported in Appendix A. The selected studies covered a time horizon ranging from 2007 to 2023 (Figure 1). The number of papers over the years shows an increasing interest of researchers in this topic since 2012.

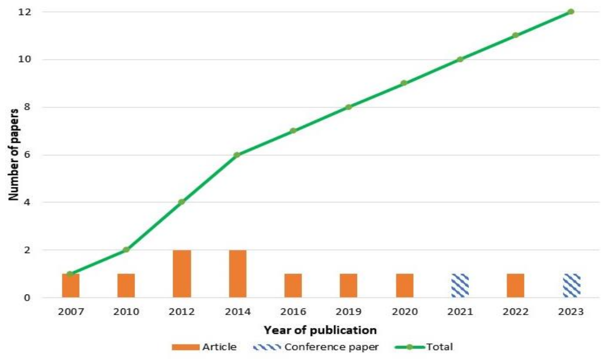

Figure 1: Time distribution of the selected papers.

To have a more precise view of the type of study of each paper, however, a further differentiation was made to understand in more detail the content of the text and the type of proposal, distinguishing models/software, frameworks, or purely conceptual analyses. About the selected papers, the types of studies identified are distributed as follows (Figure 2).

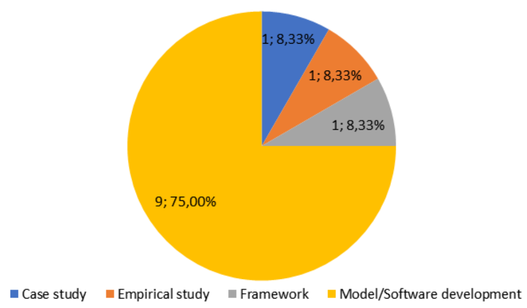

Figure 2: Types of study distribution.

As shown, proposals for new models, i.e. creating a theoretical or conceptual model that represents the ETO system or one of its processes, prevail (about 75%). Identified the process, key variables, and parameters are defined to formulate equations that describe the dynamics of the system itself. This type of study is useful for exploring, understanding, and predicting the behaviour of complex systems.

Regarding the industrial sectors involved in the studies (Figure 3), there is a prevalence of the mechanical sector, which includes, for example, the production of mechanical components, water pumps, steam turbines, or machine tools. This is followed by general manufacturing, a tag used when the category of the manufacturing sector was not specified within the study.

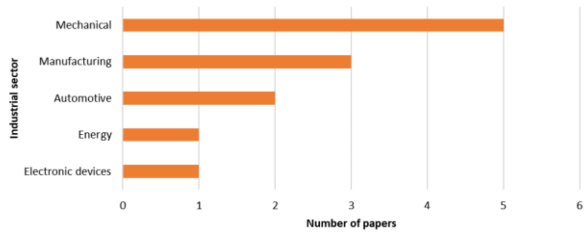

Figure 3: Industrial sector distribution of the selected papers

3.1 RQ1: Business Processes and Functions involved in ETO materials management.

Regarding the analysis of business processes and functions that characterize ETO materials management systems, each of the selected papers was classified according to the business process analysed and the related function involved. The results obtained are reported in Figure 4.

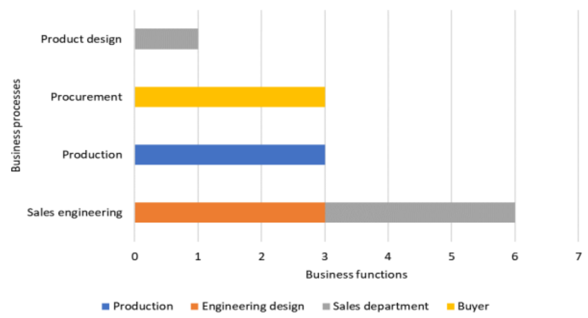

Figure 4: Business functions involved in materials management in each ETO process.

In the sales engineering process, there is the intersection of the two functions of the *sales department* (Wehlin et al., 2021), which firstly deals with the customer for the specification of the product requirements as well as the offer formulation, and the *engineering design*, which deals, in this phase, with the realization of the first outline drawings for the definition of the product characteristics. The sales engineering process is considered among the most complex processes to manage in ETO systems because it requires a great deal of effort by the company, which must not only produce the product according to the customer's requirements but also formulate an offer in an increasingly tight timeframe, coping with high uncertainty related to incomplete, inaccurate and sometimes unavailable data (Reid et al., 2019). Typically, response times to the customer are long, and sometimes both cost and time estimates for the project itself are characterized by low accuracy. It emerges from some estimates that about 60% of the total project lead time is made up of the pre-production phases because of the high complexity of the activities to be performed. In the next phase of product design, the engineering design team is involved in the realization of the overall drawings to be sent later to the production function to start the actual production activities. First, however, it is necessary to purchase materials and manage warehouse stocks: the *buyer* function is involved in this case. It is responsible for the procurement, at the right time and the best possible price, of all materials necessary for the production of parts for individual orders (Weng et al., 2020). The *buyer* function has to manage the relations with suppliers, which are crucial, especially for the purchase of critical materials or materials that have long delivery lead times, thus associated with a high level of uncertainty, as well as for the management of supplies including consumables to be stored in the warehouse. Particularly, the latter activity generates high stock holding costs when the service level is to be maintained at a high level (Radke & Tseng, 2012). Once the ordered materials have been received, thanks to the drawings received from the engineering design, the *production* function can start the manufacture of the components taking into account the tight lead times, while still maintaining high performance and quality (Centobelli et al., 2016). In contrast to the others, no reference emerged in the analysis to the process of project closure and reporting of costs incurred during activities, which is essential for the review and storage of all project data, and which involved primarily the *management* function.

3.2 RQ2: Materials Costs Approaches.

The carried-out analysis allowed us to identify the papers (8 out of 12 articles) that reported and defined approaches to modelling the relationship between materials and costs. The problem of the high complexity of cost estimation during the bidding phase or changes in customer requirements during the project is often highlighted in the literature (Hooshmand et al., 2016). The ability to provide accurate cost and delivery time estimates allows ETO companies to remain competitive in the market. Currently, however, the cost estimation process in the bidding phase is strictly dependent on key employees with crucial expert knowledge (Wehlin et al., 2021). Since customized products with specific characteristics have to be manufactured, procurement costs are higher and delivery risks are greater: for this reason, the concept of inventory planning and control is often introduced to reduce delivery lead times while trying to minimize materials management costs (Radke & Tseng, 2012). Since there are no price lists, rather suppliers must be contacted each time a product has to be purchased (Elgh, 2012) and, considering the variability of raw material prices on the market, the process of monitoring and reporting the costs incurred during the project is of crucial importance to have a good basis for estimating future projects with similar offers. Thus, it will no longer be necessary to rely only on the specific experience of a few employees (Wehlin et al., 2021), but information and knowledge can be shared across all departments of the company.

3.3 RQ3: Research Trends and Gaps Identified.

After analysing the business processes and functions involved in materials management and the approaches already developed to model, report or budget their costs, the main trends and research gaps reported in the selected studies were identified to answer RQ3. The process that most emerged from the analysis was the "**production**" process, which is analysed mainly from the point of view of improving performance. Several methods are proposed for reconfiguring the production layout (Centobelli et al., 2016), which, in ETO environments, is often inefficient and, therefore, causes excessively long lead times and delays in deliveries that result in customer dissatisfaction. The main problems that emerged from the analysis were long waiting and throughput times, high WIP (Work-In-Progress), and low visibility along the production chain due to the high complexity of the production process. Several algorithms and methods have been presented to support the traceability of materials during the production process: through the use of Industry 4.0 technologies (i.e. RFID) (Pero & Rossi, 2014) or innovative management techniques (such as the POLCA system), they promote greater control of the line to avoid unnecessary WIP queues and to properly manage priorities in the case of multiple projects (Riezebos, 2010; Telles et al., 2022). However, it would often be necessary to extend these approaches to other processes while considering the actual complexity of ETO systems to assess their actual functionality. Following this, the processes of "**sales engineering**" and "**procurement**"/ "**warehouse management**" emerge. In the first case, models and software are proposed to automate the product design and offer definition phases (Elgh, 2012, 2014): through user interfaces, customers can interact with the system themselves by defining the specifications and functional requirements and evaluating all possible configurations until they find the one that best meets their specific needs. In the end, based on the choices made, drawings are automatically made as well as the estimated cost and value offer are defined, which will be, therefore, more reliable (Wehlin et al., 2021). Through this approach, the link to the subsequent product design process is defined: to realize detailed drawings of components while reducing the risk of errors or the need for subsequent design changes, which are usually very expensive, it is necessary to integrate data properly. The main limitations are the poor possibility of customization due to the need to adapt the final design of the product to an existing one and the risk of restricting the information flow to pre-production processes. Regarding "**procurement**"/ "**warehouse management**" processes, the main focus is on defining techniques, such as mathematical models and algorithms, useful for inventory planning and stock calculation so that the level of service and stock utilization can be maximized and, at the same time, the cost of the inventory itself reduced (Radke & Tseng, 2012; Weng et al., 2020). Despite the proposed approaches, ETO systems are characterized by high complexity and variability, so the inventory planning activities are still very difficult to complete and new methods need to be developed. Unlike the others, the "**project closing and costs reporting**" process did not emerge in the analysis of the selected articles. There is, therefore, a gap in the literature compared to the proposal of methods and models that allow simplifying the processes of accurate reporting of all the costs associated with individual projects. Reporting is defined as "the process of making a statement of the expenses actually and definitively incurred for the realization of the project". This process is fundamental to define the real material consumption related to the project and, consequently, determine the actual gain, and to make the comparison with the initial forecast, identifying, where necessary, any surplus or cost reduction to identify its causes at a later stage. Following this process, it is possible to update the historical data, useful for the formulation of the offers of future projects, and to make them more accurate and reliable.

4. Discussions and future research agenda

The literature review shows that the topic of materials management in ETO production systems since about 2012 has begun to enjoy increased attention from research (Figure 1), which has been particularly involved in defining new models for efficient process management (Figure 2). Since the 1990s, the industrial sector has shifted from traditional mass production to a different production method, which, thanks to the gradual development of technology, has led to increasing customer demand for product customization, resulting in reduced volumes and increased ranges (Telles et al., 2022). Although initially, companies tried to adapt traditional management systems, such as Material Requirements Planning (MRP) or MRPII, to the new production systems, experience later showed that new methods were needed that better adapted to productions that had become no longer repetitive, rather unique, and highly complex (Strandhagen et al., 2019). Indeed, among the main features of MRPII software systems is the assumption that the production process is "standard", consisting of a well-known Bill of Materials (BoM) and a precise manufacturing process. To work properly, all information must be readily available and certain. These systems are not applicable in ETO environments mainly for the rare use of the BoM: since the products realized are highly customized, the definition of a complete BoM should be extremely time-consuming and not practically useful for future different products. In addition, there is a close relationship between customer orders and production orders, the need to control non-physical processes, the high level of detail of information, and the need to report the cost of orders.

The literature has drawn attention to the development of new methods and models in the field of ETO materials management. From the review conducted, there is evidence of a way of proceeding in which each study focuses on only one or two business functions at most (Figure 4), consequently encompassing only one or two business processes, rather than looking at the entire flow of activities. So, currently, it is not possible to proceed with an improvement and optimization of the overall process that goes from the definition of the offer to the closing and reporting of the project itself. The proposed methods and software provide solutions to the problems of individual phases (Appendix A), generally the most complex, such as sales engineering, which, as a pre-production phase, is characterized by information that is not fully defined, clear, and reliable (Reid et al., 2019). In addition to the absence of an all-encompassing framework, there is also a lack of proposals for models or methods to support the job order cost monitoring/reporting processes to make more efficient an activity that, at present, can hardly be managed because, without having the right information available, it is not possible to carry out the valorization of consumption associated with the realization of job order products. Currently, companies tend to use unstructured methods for project management and cost monitoring/reporting, such as self-made spreadsheets in which information is collected manually or a combination of these with a traditional ERP system. None of them allow for the integration of information and traceability of the entire process (Synnes & Welo, 2023). Considering the needs of the ETO sector, such as traceability of materials during the process, fast and secure exchange of information, integration between processes (Pero & Rossi, 2014), customer satisfaction in ever tighter timeframes (Centobelli et al., 2016), and detailed cost reporting of individual projects, having defined the current state and noted the existing gaps in the scientific literature, the need to develop an innovative framework is clear. It should be capable of integrating all the peculiarities of each business process involved in the project management process for an ETO company, identifying the material and non-material inputs and outputs, as well as the resources involved and the existing constraints. The framework, which addresses the key needs of ETO companies, will allow them to define and track material requirements, purchases, and consumption during the production process of typically complex and highly customized products, enabling a more accurate product revision or maintenance process, as well as proper reporting of project costs, which will help to make future cost estimates of similar products more accurate. This could potentially revolutionize the performance of activities in the ETO environment. Moreover, to strengthen and discuss the ETO needs identified in this study, it may be useful to conduct specific surveys: this would provide an excellent starting point for the creation of tools to support the project cost monitoring and reporting process to make more efficient an activity that cannot be managed properly because companies are unable to quantify the economic value associated with the job order products. The new infrastructure, once integrated with an information flow capable of keeping the cost of materials up to date, can also enable the development of an innovative software application that meets the above-mentioned needs. This will improve the overall performance of ETO activities by making the bidding phase faster and more reliable and ensuring faster response to customer requests.

5. Conclusions

Engineer-To-Order (ETO) companies produce highly customized products based on specific customer requirements. These products, being very often unique ones, generate highly variable production processes characterized by high levels of complexity. The need to have simpler, faster, and more precise systems for managing materials and reporting their costs associated with each project, although not yet addressed in detail in the literature, plays an important role for all these companies in which non-repetitive industrial activities and processes generate difficulties not only in forecasting costs but also in the subsequent phase of calculating actual expenditure, as well as the revenue obtained. This research work, methodologically based on a scoping literature review, identified the main business processes and functions involved in materials management as well as the current materials cost approaches, also highlighting the main trends and gaps in this research field. The main results of the carried-out analysis are: (i) the absence of comprehensive frameworks that considered all the processes and functions involved in the ETO organizations regarding materials management, (ii) the difficulty in integrating data and information for the proper management of physical and information flows and (iii) the lack of methods or models to carry out cost monitoring/reporting of projects to value overall profit. However, this study presents some limitations. The search strategy could be improved in different ways such as by using multiple scientific databases and defining a better set of keywords to use for the search. Moreover, given the practical nature of ETO material flow management and cost reporting, it might be useful to investigate not only the scientific literature but also other sources such as white papers, consulting companies' papers, and business/technical reports.

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Appendix A. Selected papers' analysis: main findings

Ref.	Type of Study	Tool and Method	Business process	Business function	Industrial sector	Cost reference?	Gaps Highlighted
(Yang et al., 2007)	Empirical study	Product structure standardization	Sales engineering	Engineering design	Mechanical	✓	Low degree of customization No cost estimation/ monitoring/reporting method
(Riezebos, 2010)	Model/Software development	POLCA system	Production	Production	Mechanical		Difficult to apply in a complex ETO system
(Elgh, 2012)	Framework	Automated bid preparation	Sales engineering	Sales department	Automotive	✓	No cost monitoring/reporting method
(Radke & Tseng, 2012)	Model/Software development	Mathematical model for inventory planning	Procurement	Buyer	Mechanical	✓	Only inventory costs are considered
(Elgh, 2014)	Model/Software development	Automated bid preparation	Sales engineering	Engineering design	Manufacturing	✓	No cost monitoring/reporting method
(Pero & Rossi, 2014)	Model/Software development	RFID technology for traceability	Production	Production	Energy	✓	No data-gathering sub-system No cost monitoring/reporting method
(Hooshmand et al., 2016)	Model/Software development	Cost estimation model	Sales engineering	Sales department	Automotive	✓	No cost monitoring/reporting method for all materials involved in the production processes
(Reid et al., 2019)	Model/Software development	IDEF modeling for tendering	Sales engineering	Sales department	Mechanical		The process is analysed only about the performance achieved
(Weng et al., 2020)	Model/Software development	Mathematical model for inventory planning	Procurement	Buyer	Mechanical		Low product complexity No cost balance consideration
(Wehlin et al., 2021)	Model/Software development	Automated bid preparation	Sales engineering	Engineering design, sales department	Manufacturing	✓	Cost estimation method, but not cost monitoring/reporting method
(Telles et al., 2022)	Case study	Drum-Buffer-Rope technique for managing production priorities	Production	Production	Electronic devices		Need to establish (1) standard cycle times for production operations and (2) improve production planning
(Wenzel et al., 2023)	Model/Software development	Mathematical model for inventory planning	Procurement	Buyer	Manufacturing	✓	Only inventory costs are considered