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Engineering-to-order manufacturing: A criticality analysis of key challenges and solutions based on literature review

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A B S T R A C T

Engineer-to-Order (ETO) manufacturing companies involve customised production products based on specific customer requirements, and face a significant challenge. Some of those challenges are related with this type of company's activities in production scheduling, planning and control, efficiency improvement and lead time reduction. The present study was conducted with a systematic literature review and a survey from ETO firms to identify the most frequent and critical problems. Among the most critical issues identified is the difficulty in optimising production performance (P3), with a GCI value of 16, implying that both time and cost share the same critical level. An analysis using a proposed Criticality Matrix was then performed enabling companies to prioritise decision-making and resource allocation. The results highlight the importance of adopting mass customisation strategies, innovative approaches and workflow optimisation. Continuous monitoring and analysis of criticality levels can also help ETO companies identify emerging issues and improve informed decisions. Effective communication and collaboration among stakeholders were also identified as vital. Future research could be done expanding further the study sample and developing decision-support tools for ETO manufacturing companies. This study contributes to the field by providing a new criticality matrix for ETO companies to understand better and address their production challenges, aiding in decision-making and resource allocation.

A R T I C L E I N F O

Keywords:
Communication and collaboration;
Critical factors;
Decision-making;
Engineer-to-order;
Literature review;
Production planning and control;
Production scheduling;
Resource allocation;
Workflow optimisation

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1. Introduction

1.1 Background

Engineering-to-Order (ETO) companies typically manufacture highly complex and customised products with significant engineering components that provide high value. As highlighted by Jiang and Xi, these companies utilise an ETO strategy particularly when complex structures are required to be built [1]. In general, and particularly in European Union, such companies are small or medium-sized and play essential roles in specific sectors and regions, primarily operating in international markets. ETO companies' economic development and competitiveness are crucial for their success, as they supply various industrial sectors, such as the automotive, aeronautical, and pharmaceutical/medical device industries. Their business model is centred around their ability to design, develop and manufacture products to order, delivering value to their clients [2]. One example of a sector where ETO companies are common is the mould manufacturing industry, especially tools and plastics. ETO companies face many challenges in production planning and shop floor management as product and process diversity and complexity increase system variability. These highly competitive sectors require the efficient execution of numerous activities to meet customer expectations.

Therefore, shop floor planning and operational decision-making effectiveness are essential for these companies. In addition, they must fulfil increasingly shorter delivery times defined by the market or clients, who also demand quality and lower costs. ETO companies often must also deal with a workflow that requires the quick generation of product designs, detailed bill of material and manufacturing work instructions for each order, to meet tailored customer specifications.

1.2 Scope and outline

In the context of Engineer-to-Order (ETO), companies encounter diverse tasks, high-level customisation of products, and an unpredictable market. These elements call for insightful planning and decision-making, seamlessly integrated with essential operations such as tendering and procurement, to enhance performance across their value chain. Consequently, the impetus for this investigation is threefold: (a) to assist ETO companies in honing their efficiency and effectiveness in operations, augmenting their impact and importance in a specific industrial domain and the broader economy; (b) to introduce novel strategies, methodologies, procedures, or resources to ETO companies to boost their market competitiveness; and (c) to lessen the innate challenges associated with ETO operations, particularly by enhancing their capacity to manage the volatility and intricacy within their entire value chain. A SLR was conducted to identify the main challenges and issues related to ETO companies and the methods and approaches presented in the scientific literature to resolve or mitigate these issues in the value chain of this type of company. The search for scientific literature on the topic aimed to gain knowledge about various viewpoints and holistically interpret the study's theories and models. Additionally, ETO companies, were surveyed to identify the most frequent and critical problems, with a subsequent criticality analysis using a developed criticality matrix for problems in ETO companies, offering valuable insights into industry perspectives and potential avenues for improvement. This paper is structured as follows: Section 1 presents an overview of the study's background and motivation.

2. Materials and methods

2.1 Research methodology

An SLR was developed to identify ETO companies' difficulties and the technical and scientific solutions proposed to address them, followed by a survey of ETO companies to assess the criticality of the identified problems in those organisations.

Unlike narrative reviews, the SLR aim to answer a specific research question through a planned and structured approach to identifying, selecting, and critically appraising relevant studies [3]. By analysing and synthesising different authors findings, a comprehensive understanding of the existing body of work is gained, gaps to explore are identified, and conclusions are drawn on what is known and not known [4]. The review followed the PRISMA [5] guidance approach, with specific eligible criteria that included: papers discussing ETO problems, process planning, manufacturing related articles, production planning and control, and articles published in English. Articles that did not meet these criteria were excluded. The relevant studies were identified by searching digital databases, such as Web of Science and Scopus, as shown in Table 1. Articles published between January 2017 and April 2022 were the ones in this study considered, using search terms such as "engineer* to order" AND "variab*" OR "uncertaint*" OR "complex*" AND "produc* control" OR "plan*" OR "schedul*" OR "produc* process" OR "workflow*" OR "shop-floor*" OR "digital*" OR "problem*" OR "issue*" OR "constraint*" OR "inefficient*" NOT "ship*" OR "building*".

Table 1 Databases used for the search

Database	Search Terms
Web of Science	TS = ("engineer* to order") AND TS = (variab* OR uncertaint* OR complex*) AND TS = ("produc* control" OR plan* OR schedul* OR "produc* process" OR workflow* OR "shop-floor*" OR digital* OR problem* OR issue* OR constraint* OR inefficient*) NOT TS = (ship* OR building*)
Scopus	TITLE-ABS-KEY("engineer* to order") AND TITLE-ABS-KEY(variab* OR uncertaint* OR complex*) AND TITLE-ABS-KEY("produc* control" OR plan* OR schedul* OR "produc* process" OR workflow* OR "shop-floor*" OR digital* OR problem* OR issue* OR constraint* OR inefficient*) AND NOT(ship* OR building*) AND (LIMIT-TO(DOCTYPE,"ar") OR LIMIT-TO(DOCTYPE,"cp")) AND (LIMIT-TO(LANGUAGE,"English"))

The study search yielded 83 WoS publications and 57 Scopus publications in a total of 140 potentially relevant publications, from which 32 were duplicated as shown in Fig. 1. From the initial 108 publications analysed for inclusion, 62 articles did not meet the selection criteria due to their publication dates falling outside of the 2017-2022 range, thus leading to their exclusion. This process yielded 46 potentially most relevant references to undergo a comprehensive in-depth analysis, out of which only 18 were deemed pertinent. Further to this rigorous analysis, six articles were identified and subsequently included in the study. Fig. 1 shows the flow of citations through the systematic review process.

The final sample size of 24 papers can be considered a robust number for this analysis, as similar sample sizes have been used in other studies such as 19 papers in nursing studies [6], 23 papers in learning management [7], and 23 papers in project management studies [8]. In the following section, the results of the in-depth content analysis of the identified articles are synthesised, focusing on the general framework and competitive environment in which ETO operates and, in the challenges and issues faced by this type of company, including its principal characteristics and organisation.

In addition to the SLR, a survey was also conducted among ETO companies to better understand the frequency and the criticality of the identified problems. This survey aimed to check the findings of the SLR and provide any new real-world perspectives on the challenges encountered in ETO environments. The collected data were analysed using a proposed criticality matrix to assess the identified problems potentially severe impact and prioritise potential solutions. This approach allowed for a more comprehensive understanding of all the identified problems and issues faced by ETO companies, providing an informed potential action.

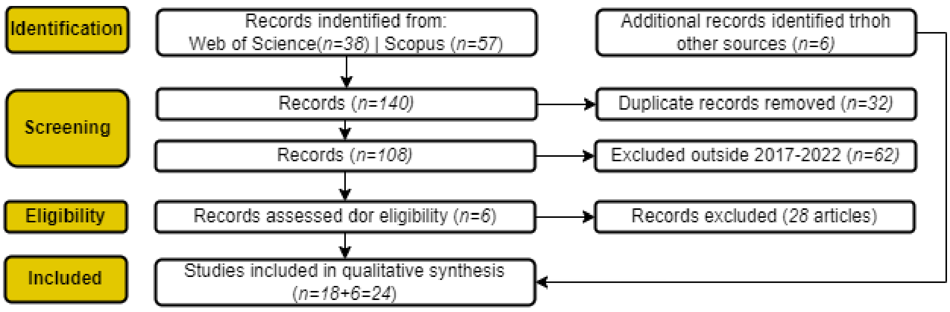

Fig. 1 A schematic flow chart diagram of the selected studies

2.2 A concept map approach of ETOs challenges and solutions

ETO companies specialise in fabricating high-value-added customised products in low volumes, typically small batches or one-of-a-kind products, as shown in Fig. 2.

As project-based organisations, ETO companies focus mainly on designing and manufacturing new products, involving a complex and highly specialised process that demands qualified and flexible workers [9]. Moreover, ETO companies are customer-centric [10], involving strong customer participation in product development. However, due to the initial phase's complexity and uncertainty in customer product characteristics, raw material purchase and product manufacturing only begin after the customer confirms the order quotation.

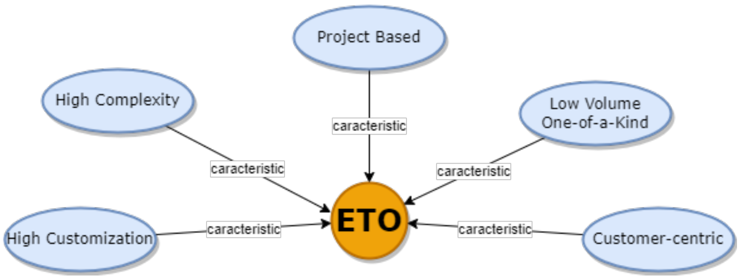

Fig. 2 Main attributes of ETO

ETO Potential key challenges

The demand for increasingly customised products has resulted in the need for better performance in ETO companies [11]. However, the discrete nature of shop floor workflows in ETO companies poses a significant management challenge requiring higher decision-making resilience to workflow performance [12]. The tactical-level management of value chain information can also be considered another critical issue in the dynamic environment of ETO companies [13]. During the contracting stage, uncertainties about costs and delivery date forecasts are typical, resulting in higher manufacturing costs [14], longer lead times, higher inventory costs, transportation costs, and other supply risks. Planning in ETO companies is complex, given the combination of multiple technical responsibility areas and the difficulty in predicting workload resources and lead times [15]. Customers can be involved in all project stages, such as design, production, assembly and testing [16]. These challenges often result in manufacturing process delays due to changes made during the project's progress [17]. Late changes in engineering design can cause costs increases and affect resource allocation along the value chain, according to Gosling *et al.* [18]. The involvement of customers and the various interactions place a high demand on production planning and control activities [19]. Also, as noted by Akcay *et al.* [20]. One-of-a-kind products or low-volume batches increase the number of jobs pending in manufacturing.

Developing a concept map for scientific and technological solutions

A thorough comprehension of ETO organisations and their challenges can be significantly enhanced by adopting innovative and engaging visual representations, such as concept maps. Unlike traditional tables, these maps can provide an intuitive and interactive means of conveying detailed information.

Derived from the problem table resulting from the SLR conducted in the research, an ETO domain, concept map can be proven beneficial for identifying and examining ETOs diverse issues, weaknesses, and areas warranting further investigation [21]. From Fortes *et al.* [21], Fig. 3, depicts a multi-layered concept map, with the ETO companies and their characteristics placed at the centre, encircled by a second ring that contains the surrounding issues. The third ring introduces the authors' proposals, and the outermost ring emphasises the contributions and limitations of the studies. This layout was design to enhance the understanding of problem areas, underline the need for further research, and to promote the development of adaptive strategies to tackle ETO organisations' multifaceted challenges. This concept map employs five distinct colours and three unique shapes to differentiate identified distinct categories. Blue balloons represent the characteristics of ETO companies; white balloons signify the issues to be addressed; yellow balloons indicate approaches; green balloons denote contributions; and red balloons symbolise weaknesses.

For example, the item "Bid solution uncertain", as presented in the study by Sylla *et al.* [22], is represented by a white balloon, signifying the issue that needs to be addressed. Subsequent yellow rectangles illustrate the approach of "a multi-criteria approach to bid solution uncertainty". For example, a green balloon showcases contributions, such as "providing bid solutions with accurate and timely replies", whilst a red balloon points out weaknesses, like "single case study with limited data". This visual approach intends to enable readers to effortlessly identify the categories of each item and their relationships with one another. Furthermore, connections between balloons can be established to illustrate the identified links between items. For instance, a connection between balloons one and two can be drawn, as both pertain to uncertain bid solutions.

So, concept maps offer a compelling and effective way of organising and presenting complex information [23] related to ETO organisations' challenges and potential solutions. By employing a visually appealing and interactive layout, these maps can facilitate a deeper understanding of the issues, approaches, contributions, and weaknesses within this field, ultimately encouraging further investigation and development of comprehensive strategies to address the dynamic challenges faced by ETO companies.

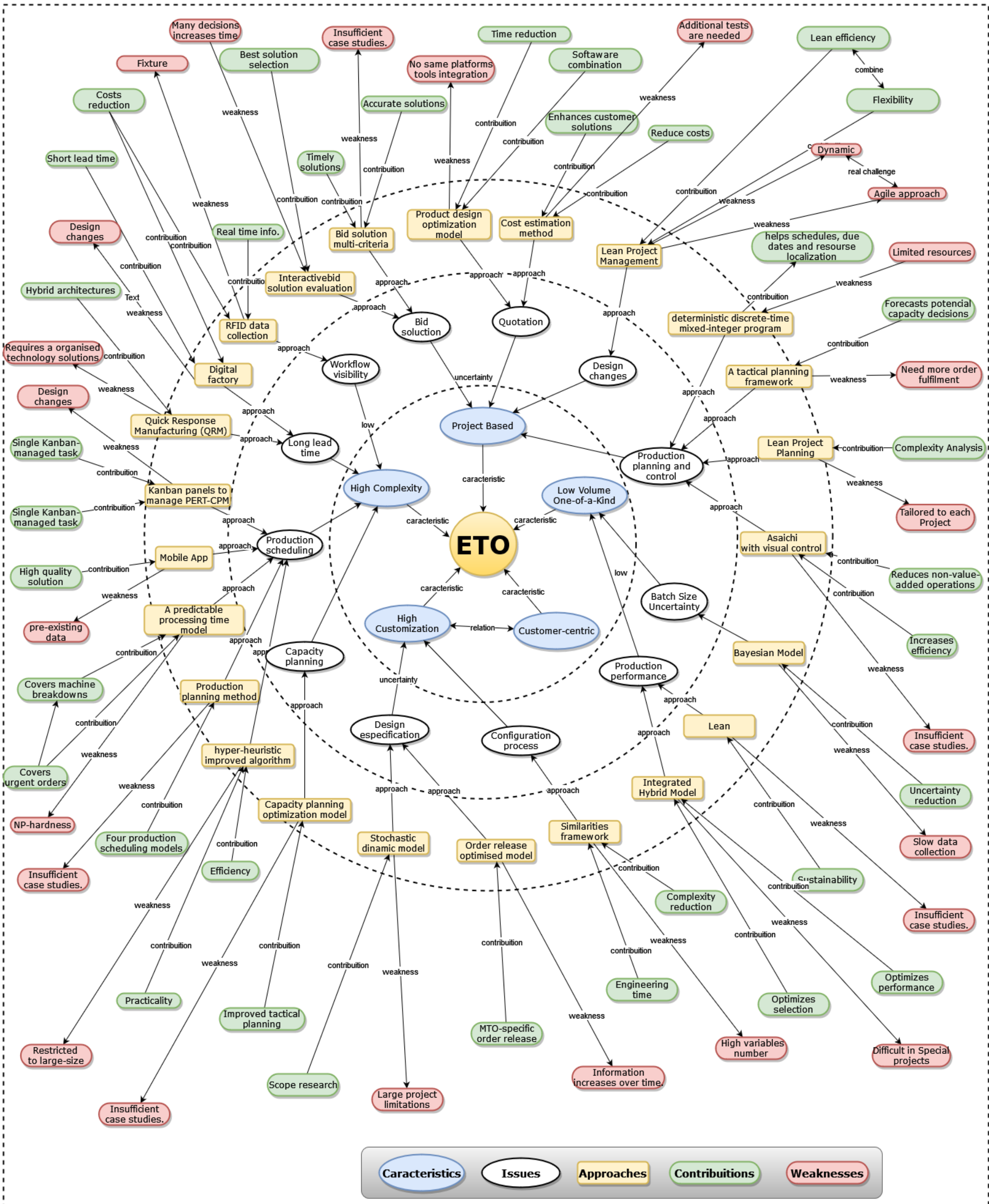

Fig. 1 ETO concept diagram [21]

3. Results and discussion: Criticality analysis of ETO companies' problems

The systematic literature review (SLR) results and ETOS's companies problem assessment survey examined the frequency and identified problems impact these organisations encounter, establishing the associated criticality. To ensure a diverse sample survey was developed specifically targeting high-level professionals such as managers, department directors, and project managers from a diverse range of ETO companies, including different industry sectors, sizes, and geographical locations. This investigation uncovered new valuables insights, enabling stakeholders to better understand the pressing concerns affecting ETO businesses. In addition, insights into pressing issues in ETO companies, allowing stakeholders to prioritise efforts, develop effective strategies, and improve performance and competitiveness within the sector can be provided by the proposed "Criticality Analysis of ETO Company Problems" table.

3.1 Problem frequency assessment

The analysis involved assessing the relative citation frequencies of each problem identified in the SLR *cf* and comparing them to the average organisational occurrence rankings reported by the study survey *fr* to check the theoretical known SLR findings and identify any new current problems. This study's results discovered no additional problems, and all problems were reported as occurring in practice. Table 2 lists the 14 problems discovered through the SLR, where problem P10 (Production Scheduling) emerged as the most cited, followed by P11 (Production Planning and Control), with P2 (Tender Proposal), P3 (Production Performance), P12 (Product Specification), and P14 (Lead Time) in third place. In terms of reported frequency *fr* all problems were assessed as existing validating the SLR identified problems and revealing that 12 of the 14 problems (P1, P2, P4, P5, P7, P8, P9, P10, P11, P12, P13, and P14) were equally frequently assessed with P3 (Production Performance) the most frequent problem and P6 (Unstructured Knowledge) the least concerned from the surveyed companies' perspective.

Table 2 Criticality analysis of ETO company problems

Item	Designation	Description	*pf* (%)	Ranking	*fr* (%)	Ranking	Deviation
P1	Capacity Planning	Difficulty in adapting existing capacities to new product development and production plans.	4	4th	7	2nd	+2
P2	Tender Proposal	Limitations in accurately defining tender proposals due to uncertainty.	8	3rd	7	2nd	+1
P3	Production Performance	Difficulty in process optimisation.	8	3rd	10	1st	+2
P4	Workflow Visibility	Difficulty in visualising workload and supporting decision-making in a dynamic shop floor.	4	4th	7	2nd	+2
P5	Configuration Process	Frequent constraints on workflow configuration due to resource scarcity.	4	4th	7	2nd	+2
P6	Unstructured Knowledge	Inefficient reuse of design knowledge for new products.	4	4th	5	3rd	+1
P7	Lot Size Uncertainty	Uncertainty of lot size.	4	4th	7	2nd	+2
P8	Quotation	Difficulty in product design optimisation, influencing quotations.	4	4th	7	2nd	+2
P9	Workflow	Information flow failures, limiting collaboration and operational performance.	4	4th	7	2nd	+2
P10	Production Scheduling	Difficulty in defining optimal job sequences for production.	21	1st	7	2nd	-1
P11	Production Planning & Control	Addressing Variability in Operation Execution Times in Manufacturing and Assembly Processes	17	2nd	7	2nd	0
P12	Product Specification	Lack of information and detail in customer-provided product specifications.	8	3rd	7	2nd	+1
P13	Customer Changes	Late design changes due to customer-imposed alterations.	4	4th	7	2nd	+2
P14	Lead Time	Long execution time.	8	3rd	7	2nd	+1

pf – published frequencies (Scopus, Web of Science); *fr* – frequency as reported in the survey; *Dif* – difference: *Dif* = *fp* – *fr*

So, upon examining the table, several conclusions can be drawn regarding the criticality of problems ETO companies face. First, comparing published frequencies *pf* from the Scopus and Web of Science databases with the frequencies reported in the survey *fr*, which included 12 participating ETOs companies, reveals some discrepancies between the literature and the real-world challenges experienced by these firms.

Table 2 results highlight that Production Scheduling (P10) and Production Planning & Control (P11) are the most critical issues for ETO companies, as evidenced by their high published frequencies (21 % and 17 %, respectively) and their shared second positions in the survey. These findings, indicate that these issues are consistently recognised as significant challenges in academic literature and industry practice. However, most of the problems display a positive deviation in their rankings between the published frequencies *pf* and the frequencies reported in the survey (*fr*), suggesting that the participating ETO companies perceive these issues to be more critical than what is reflected in the literature. This discrepancy could imply that the existing literature must fully capture ETO companies' unique challenges or that ETO practitioners are more aware of the issues within their sector. Considering these findings, further research is recommended to explore the specific challenges faced by ETO companies in greater depth and foster closer collaboration between practitioners and academics. This collaboration can help ensure that the literature accurately reflects the practical issues experienced in the field. By addressing this gap, ETO companies can better understand and mitigate their challenges, improving their overall performance and competitiveness.

Therefore, by focusing on the most frequent concerned issues, such as Production Scheduling (P10) and Production Planning & Control (P11), researchers can contribute to developing more practical solutions and strategies, enhancing the sector's ability to tackle the complex problems inherent in ETO operations.

Moreover, the detailed examination of the impact on the field of each problem can provide valuable insights into the prioritization of challenges faced by ETO companies, guiding future research and decision-making in the sector.

3.2 Analysis of ETO problem criticality

This session analysis the critical [24] level of the ETO companies' problems to prioritise ETOs organisations' challenges. Here, the criticality assessment approach is based on the probability measure by the frequency assessment and impact of the identified problems. It is employed to assist companies in better understanding the challenges they face and develop targeted strategies for addressing them. Furthermore, this type of analysis can allow a more effective allocation of resources and informed decision-making, improving the overall performance and success of ETO projects.

Table 3 presents the proposed matrix for evaluating the criticality level of the identified ETOs problems. The criticality index *CI* results from the intersection of the row probability *P* and the column impact *I*, where the values are multiplied, thus obtaining the criticality level through the general Eq. 1.

$$CI = P \times I \tag{1}$$

Table 3 Risk matrix (Probability/Impact matrix)

Probability (P)	5	0	5	10	15	20	25
	4	0	4	8	12	16	20
	3	0	3	6	9	12	15
	2	0	2	4	6	8	10
	1	0	1	2	3	4	5
	0	0	0	0	0	0	0
Probability/Impact		0	1	2	3	4	5
		Impact (*I*)					
Non-existent/Very Low [0, 4]	Low [4, 6]	Moderate [6, 12]	High [12, 16]	Very High [16, 25]			

The criticality level of problems may vary among organisations, resulting in different evaluations based on each company's specific situation, as demonstrated in Table 4.

Table 4 Specific organisational evaluation results

Issue ETO1	*P*	cI_{ETO1}	tI_{ETO1}	*OCI*	Issue ETO2	*P*	cI_{ETO2}	tI_{ETO2}	*OCI*	Issue ETO3	*P*	cI_{ETO3}	tI_{ETO3}	*OCI*
P1	2	2	4	8	P1	2	5	4	10	P1	2	4	4	8
P2	2	3	4	8	P2	2	4	2	8	P2	2	2	2	4
P3	3	3	5	15	P3	2	5	2	10	P3	4	5	2	20
P4	2	1	4	8	P4	2	2	3	6	P4	2	4	3	8
P5	3	4	4	12	P5	3	5	4	15	P5	4	5	4	20
P6	1	1	3	3	P6	2	1	2	4	P6	3	1	2	6
P7	1	1	2	2	P7	2	2	2	4	P7	2	4	2	8
P8	2	3	4	8	P8	2	5	5	10	P8	2	2	5	10
P9	1	4	5	5	P9	2	3	5	10	P9	2	4	5	10
P10	1	1	2	2	P10	2	3	1	6	P10	2	5	1	10
P11	2	3	3	6	P11	2	3	1	6	P11	2	5	1	10
P12	3	1	4	12	P12	3	5	5	15	P12	2	5	5	10
P13	3	4	5	15	P13	2	5	5	10	P13	2	5	5	10
P14	3	5	1	15	P14	3	5	1	15	P14	3	2	1	6
ETO4	*P*	cI_{ETO4}	tI_{ETO4}	*OCI*	ETO5	*P*	cI_{ETO5}	tI_{ETO5}	*OCI*	ETO6	*P*	cI_{ETO6}	tI_{ETO6}	*OCI*
P1	3	5	4	15	P1	3	3	3	9	P1	4	3	5	20
P2	3	3	3	9	P2	2	3	3	6	P2	3	2	4	12
P3	4	3	3	12	P3	3	2	3	9	P3	5	4	5	25
P4	3	4	3	12	P4	3	3	3	9	P4	5	3	5	25
P5	4	4	3	16	P5	3	3	2	9	P5	4	2	5	20
P6	4	3	1	12	P6	3	3	3	9	P6	2	1	2	4
P7	3	3	4	12	P7	3	3	3	9	P7	2	1	2	4
P8	4	4	3	16	P8	3	2	2	6	P8	4	2	2	8
P9	4	4	4	16	P9	3	3	3	9	P9	2	3	5	10
P10	4	2	4	16	P10	3	3	3	9	P10	2	2	3	6
P11	3	3	4	12	P11	4	3	2	12	P11	2	2	4	8
P12	4	4	4	16	P12	2	2	3	6	P12	5	2	5	25
P13	4	4	5	20	P13	2	3	2	6	P13	4	2	5	20
P14	3	4	5	15	P14	2	3	3	6	P14	5	3	4	20
ETO7	*P*	cI_{ETO7}	tI_{ETO7}	*OCI*	ETO8	*P*	cI_{ETO8}	tI_{ETO8}	*OCI*	ETO9	*P*	cI_{ETO9}	tI_{ETO9}	*OCI*
P1	3	3	3	9	P1	4	4	5	20	P1	2	2	4	8
P2	1	1	1	1	P2	4	4	5	20	P2	2	3	2	6
P3	5	4	3	20	P3	4	3	5	20	P3	3	4	5	15
P4	3	1	1	3	P4	5	5	5	25	P4	3	4	5	15
P5	1	2	2	2	P5	3	3	3	9	P5	2	4	4	8
P6	1	1	1	1	P6	1	1	1	1	P6	1	4	5	5
P7	1	1	2	2	P7	1	1	1	1	P7	5	3	4	20
P8	1	1	1	1	P8	4	5	4	20	P8	5	4	4	20
P9	3	1	1	3	P9	4	4	4	16	P9	5	4	5	25
P10	2	2	2	4	P10	1	1	1	1	P10	3	3	3	9
P11	3	3	2	9	P11	3	3	5	15	P11	2	3	5	10
P12	2	3	1	6	P12	3	3	4	12	P12	2	2	2	4
P13	2	2	4	8	P13	3	3	4	12	P13	3	4	4	12
P14	1	1	1	1	P14	4	3	5	20	P14	3	3	4	12
ETO10	*P*	cI_{ET10}	tI_{ET10}	*OCI*	ETO11	*P*	cI_{ET11}	tI_{ET11}	*OCI*	ETO12	*P*	cI_{ET12}	tI_{ET12}	*OCI*
P1	5	4	5	25	P1	4	4	4	16	P1	2	4	4	8
P2	4	3	4	16	P2	4	5	4	20	P2	3	5	4	15
P3	5	5	5	25	P3	3	4	5	15	P3	3	5	4	15
P4	5	5	4	25	P4	4	3	3	12	P4	3	5	4	15
P5	5	5	5	25	P5	3	4	5	15	P5	3	5	4	15
P6	2	1	1	2	P6	3	2	2	6	P6	3	5	4	15
P7	4	1	1	4	P7	4	4	3	16	P7	2	4	4	8
P8	2	2	4	8	P8	4	4	4	16	P8	3	5	4	15
P9	2	2	2	4	P9	4	4	4	16	P9	3	5	4	15
P10	3	4	4	12	P10	4	5	4	20	P10	3	5	4	15
P11	5	5	5	25	P11	5	5	5	25	P11	3	5	4	15
P12	2	2	2	4	P12	4	5	4	20	P12	2	5	4	10
P13	4	3	2	12	P13	4	5	4	20	P13	3	5	4	15
P14	4	4	4	16	P14	4	5	5	20	P14	3	5	4	15

P – Probability; *cI* – Cost Impact; *tI* – Time Impact; *OCI* – Organizational Criticality Index

Therefore, their specific values may differ from the general average trend values. The Organisational Criticality Index *OCI* results from the multiplication of the problem reported frequency with the highest value among its reported impacts on costs $cI(\mathrm{x})$ or time $tI(\mathrm{x})$. For the analysis of the general criticality index *GCI* of each identified problem, the approximate average level of reported occurrence frequency *of* was similarly multiplied by the average impacts on costs cI and time tI for each identified problem using Eqs. 2 to 4.

$$of = \frac{(frETO1 + \ldots + fr\,ETOn)}{n} \tag{2}$$

$$cI = \frac{(cIETO1 + \ldots . + cIETOn)}{n} \tag{3}$$

$$tI = \frac{(tIETO1 + \ldots + tIETOn)}{n} \tag{4}$$

Table 5 summarises the criticality levels obtained for each problem, identifying the impact variable that most contributed to its value through time t or cost c.

Based on the findings from Table 5, the following conclusions can be drawn in the context of ETO companies. First, our analysis of the *GCI* highlights the key challenges that significantly impact these organisations in terms of time t and cost c. This understanding can enable ETO companies to develop targeted strategies and address these critical issues effectively, thereby enhancing their overall performance and competitiveness in the market.

These results demonstrate that several problems substantially impact ETO companies' performance. As noted by Leksic, the performance of an ETO company is directly tied to the efficiency of its production process, reinforcing the magnitude of the identified problems in this study [25]. Among the most critical issues identified is the difficulty in optimising production performance (P3), with a *GCI* value of 16tc meaning that both time and cost share the same critical level. This challenge arises from the highly customised nature of ETO products, which necessitates constant adaptation of manufacturing processes to meet the unique requirements of each project. Consequently, achieving the desired quality standards may require increased time and cost.

Capacity planning (P1) is another significant challenge that the surveyed ETOs companies face, with a *GCI* value of 12tc. This issue stems from the difficulty in aligning existing capacities with planning new product development and their introduction into production. As a result, ETO companies must diligently allocate resources and manage production schedules to cater to each customer's specific needs, which may pressure the overall capacity planning process.

Moreover, the analysis emphasises the importance of the configuration process (P5), which has a *GCI* value of 12tc. Frequent constraints in the workflow configuration process may occur due to the scarcity of resources concerning planned and ongoing works. The customer-centric approach of ETO companies exacerbates this issue, as accommodating unique customer requirements may lead to frequent changes and adjustments in the workflow configuration.

Table 5 Level of General Criticality Index (*GCI*)

12 ETO	Average Frequency Index of ETO Survey			*GCI*
Item	*fo*	*cI*	*tI*	
P1	3	4	4	*12tc*
P2	3	3	3	*9tc*
P3	4	4	4	*16tc*
P4	3	3	4	*12t*
P5	3	4	4	*12tc*
P6	2	2	2	*4tc*
P7	3	2	3	*9t*
P8	3	3	4	*12t*
P9	3	3	4	*12t*
P10	3	3	3	*9tc*
P11	3	4	3	*12c*
P12	3	3	4	*12t*
P13	3	4	4	*12tc*
P14	3	4	3	*12c*

tI - time impact; *cI* - cost impact

Additionally, the impact of customer-imposed changes on product design (P13) features prominently in our findings, with a *GCI* value of 12*tc*. Late changes in product design can disrupt the manufacturing process, resulting in delays and increased costs. Therefore, ETO companies must establish strategies to manage and minimise the impact of these changes on their operations.
Our analysis results also indicate that several other challenges possess moderate to high levels of criticality for ETO companies. These include workflow visibility (P4), the uncertainty of batch size (P7), pricing (P8), information flow failures (P9), production scheduling (P10), production planning and control (P11), product specification (P12), and lead time (P14). Each of these challenges is directly or indirectly influenced by the unique characteristics of ETO companies, such as their customer-centric approach, project-based operations, high customisation, low volume, extended lead times, high complexity, and high variability.

In conclusion, our examination of the criticality index for various issues faced by ETO companies emphasises the need for these organisations to recognise and address the challenges arising from their distinctive operational characteristics. Furthermore, by comprehending the criticality of these issues concerning time and cost, ETO companies can devise targeted strategies and solutions to improve their overall performance [26].

Potential strategies to tackle these challenges may include adopting lean management practices, enhanced communication and coordination among different departments, investment in employee training and development, and implementing advanced tools and technologies to boost process efficiency [27]. By addressing the critical issues identified in our study and considering the unique characteristics of ETO companies, it is feasible to enhance operational efficiency, reduce costs and lead times, and ultimately increase customer satisfaction and market competitiveness.

4. Conclusion

Analysing ETO companies' challenges highlights the importance of understanding and addressing critical factors that influence ETO manufacturing systems. By adopting mass customisation strategies and assessing problem criticality, ETO companies might more efficiently allocate resources, thereby improving time and cost management. Furthermore, focus on resource management, innovative approaches, and workflow optimisation will allow ETO companies to adapt to customer demands, increasing satisfaction and competitiveness. This study conducted an SLR and survey of ETO companies to gain insights into problem frequency and criticality. Consistent issues include production scheduling, planning and control, efficiency, and lead time reduction. The criticality analysis enables ETO companies to understand problem implications and prioritise decision-making and resource allocation. Addressing the significant criticality problems will minimise negative consequences on ETO project success. The cooperation between industry and academia is crucial for bridging the gap between theoretical knowledge and practical implementation. Continuous monitoring and analysis of criticality indices will aid ETO companies in identifying emerging issues and make informed decisions throughout projects. Balancing high and low criticality problems is crucial to avoid unexpected complications. By understanding ETOs problem criticality and considering Industry 4.0 paradigms, ETO companies can develop targeted strategies for risk reduction and workflow resilience. Effective communication and collaboration within ETO companies and with external stakeholders are vital. Continuous investment in research and development, employee training, and advanced technology adoption ensures long-term success. In addition, fostering solid collaborations between industry and academia addresses critical challenges more effectively. This research finding suggests that ETO companies should improve resource efficiency, adopt innovative management methods, and optimise workflows. Methods such as the implementation of Lean Management principles, which are proven to enhance production performance by improving quality, reducing costs and shortening production times [28], could further augment ETO companies' performance. In addition, continuous monitoring and analysis of criticality indices will aid in identifying emerging issues and making more informed decisions throughout the ETO project lifecycle. As a future proposal, it is recommended to explore the development of a model proposal aimed at improving or optimising the shop floor management process to mitigate the identified problems. This proposal would involve the design, implementation, and validation of a comprehensive framework that integrates resource allocation, workflow optimisation, and technology adoption, specifically tailored for the unique challenges faced by ETO companies. This model could facilitate continuous improvement and drive sustainable growth within the ETO industry by offering practical guidelines and actionable strategies.

References

[1] Jiang, C., Xi, J.T. (2019). Dynamic scheduling in the engineer-to-order (ETO) assembly process by the combined immune algorithm and simulated annealing method, *Advances in Production Engineering & Management,* Vol. 14, No. 3, 271-283, doi: 10.14743/apem2019.3.327.

[2] Brachmann, R., Kolisch, R. (2021). The impact of flexibility on engineer-to-order production planning, *International Journal of Production Economics,* Vol. 239, No. 108183, doi: 10.1016/j.ijpe.2021.108183.

[3] Rother, E.T. (2007). Systematic literature review X narrative review, *Acta Paulista de Enfermagem,* Vol. 20, No. 2, 5-6, doi: 10.1590/S0103-21002007000200001.

[4] Xiao, Y., Watson, M. (2019). Guidance on conducting a systematic literature review, *Journal of Planning Education and Research,* Vol. 39, No. 1, 93-112, doi: 10.1177/0739456X17723971.

[5] Page, M.J., McKenzie, J.E., Bossuyt, P.M., Boutron, I., Hoffmann, T.C., Mulrow, C.D., Shamseer, L., Tetzlaff, J.M., Akl, E.A., Brennan, S.E., Chou, R., Glanville, J., Grimshaw, J.M., Hróbjartsson, A., Lalu, M.M., Li, T., Loder, E.W., Mayo-Wilson, E., McDonald, S., McGuinness, L.A., Stewart, L.A., Thomas, J., Tricco, A.C., Welch, V.A., Whiting, P., Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews, *International Journal of Surgery,* Vol. 88, Article No. 105906, doi: 10.1016/j.ijsu.2021.105906.

[6] McCutcheon, K., Lohan, M., Traynor, M., Martin, D. (2015). A systematic review evaluating the impact of online or blended learning vs. face-to-face learning of clinical skills in undergraduate nurse education, *Journal of Advanced Nursing,* Vol. 71, No. 2, 255-270, doi: 10.1111/jan.12509.

[7] Turnbull, D., Chugh, R. Luck, J. (2021). Learning management systems: A review of the research methodology literature in Australia and China, *International Journal of Research & Method in Education,* Vol. 44, No. 4, 164-178, doi: 10.1080/1743727X.2020.1737002.

[8] Raharjo, T., Purwandari, B. (2020). Agile project management challenges and mapping solutions: A systematic literature review, In: *Proceedings of the 3rd International Conference on Software Engineering and Information Management,* Sydney, Australia, 123-129, doi: 10.1145/3378936.3378949.

[9] Duda, J., Macioł, A., Jędrusik, S., Rębiasz, B., Stawowy, A., Sopińska-Lenart, M. (2021). Quick response manufacturing for high mix, low volume, high complexity manufacturers, *Management and Production Engineering Review,* Vol. 12, No. 1, 72-84, doi: 10.24425/mper.2021.136873.

[10] Papinniemi, J., Fritz, J., Hannola, L., Denger, A., Lampela, H. (2014). Lifecycle-based requirements of product-service system in customer-centric manufacturing. In: Fukuda, S., Bernard, A., Gurumoorthy, B., Bouras, A. (eds.), *Product lifecycle management for a global market, PLM 2014, IFIP Advances in information and communication technology,* Vol. 442. Springer, Berlin, Heidelberg, 435-444, doi: 10.1007/978-3-662-45937-9_43.

[11] Sjøbakk, B., Bakås, O., Bondarenko, O., Kamran, T. (2015). Designing a performance measurement system to support materials management in engineer-to-order: A case study, *Advances in Manufacturing*, Vol. 3, 111-122, doi: 10.1007/s40436-015-0109-2.

[12] Husejnagić, D., Sluga, A. (2015). A conceptual framework for a ubiquitous autonomous work system in the Engineer-To-Order environment, *International Journal of Advanced Manufacturing Technology,* Vol. 78, 1971-1988, doi: 10.1007/s00170-015-6798-7.

[13] Cigolini, R., Gosling, J., Iyer, A., Senicheva, O. (2020). Supply chain management in construction and engineer-to-order industries, *Production Planning & Control,* Vol. 33, No. 9-10, 803-810, doi: 10.1080/09537287.2020.1837981.

[14] Villar-Fidalgo, L., Espinosa Escudero, M.d.M., Dominguez Somonte, M. (2019). Applying kaizen to the schedule in a concurrent environment, *Production Planning & Control,* Vol. 30, No. 8, 624-638, doi: 10.1080/09537287.2019.1566281.

[15] Cannas, V.G., Pero, M., Pozzi, R., Rossi, T. (2018). An empirical application of lean management techniques to support ETO design and production planning, *IFAC-PapersOnLine,* Vol. 51, No. 11, 134-139, doi: 10.1016/j.ifacol.2018.08.247.

[16] Zheng, P., Xu, X., Yu, S., Liu, C. (2017). Personalized product configuration framework in an adaptable open architecture product platform, *Journal of Manufacturing Systems*, Vol. 43, Part 3, 422-435, doi: 10.1016/j.jmsy.2017.03.010.

[17] Vaagen, H., Ballard, G. (2021). Lean and flexible project delivery, *Applied Sciences,* Vol. 11, No. 19, Article No. 9287, doi: 10.3390/app11199287.

[18] Gosling, J., Towill, D.R., Naim, M.M., Dainty, A.R.J. (2015). Principles for the design and operation of engineer-to-order supply chains in the construction sector, *Production Planning & Control,* Vol. 26, No. 3, 203-218, doi: 10.1080/09537287.2014.880816.

[19] Gössinger, R., Plitt, J. (2019). Order release in ETO systems - A basic optimization-based approach, *IFAC-Papers OnLine,* Vol. 52, No. 13, 2207-2212, doi: 10.1016/j.ifacol.2019.11.533.

[20] Xie, W., Nelson, B.L., Barton, R.R. (2014). Statistical uncertainty analysis for stochastic simulation with dependent input models, In: *Proceedings of the Winter Simulation Conference 2014*, Savannah, USA, 674-685, doi:

10.1109/WSC.2014.7019931.
[21] Fortes, C.S., Tenera, A.B., Cunha, P.F. (2023). Engineer-to-order challenges and issues: A systematic literature review of the manufacturing industry, *Procedia Computer Science,* Vol. 219, 1727-1734, doi: 10.1016/j.procs.2023.01.467.
[22] Sylla, A., Vareilles, E., Coudert, T., Aldanondo, M., Geneste, L., Beauregard, Y. (2017). ETO bid solutions definition and selection using configuration models and a multi-criteria approach. In: *Proceedings of 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM),* Singapore, 1833-1837, doi: 10.1109/IEEM.2017.8290208.
[23] Formoso, C., Tommelein, I.D., Saurin, T.A., Koskela, L., Fireman, M., Barth, K., Bataglin, F., Viana, D., Coelho, R., Singh, V., Zani, C., Ransolin, N., Disconzi, C. (2021). Slack in construction - Part 1: Core concepts, In: *Proceedings of 29th Annual Conference of the International Group for Lean Construction (IGLC)*, Lima, Peru, 187-196, doi: 10.24928/2021/0183.
[24] Theoharidou, M., Kotzanikolaou, P., Gritzalis, D. (2009). Risk-based criticality analysis, In: Palmer, C., Shenoi, S. (eds.), *Critical infrastructure protection III. ICCIP 2009, IFIP Advances in information and communication technology,* Vol. 311, Springer, Berlin, Heidelberg, Germany, 3-13, doi: 10.1007/978-3-642-04798-5_3.
[25] Leksic, I., Stefanic, N., Veza, I. (2020). The impact of using different lean manufacturing tools on waste reduction, *Advances in Production Engineering & Management,* Vol. 15, No. 1, 81-92, doi: 10.14743/apem2020.1.351.
[26] Larsson, D., Ratnayake, R.M.C. (2021). Implementation of 5S+S for knowledge work in engineering projects. In: In: Dolgui, A., Bernard, A., Lemoine, D., von Cieminski, G., Romero, D. (eds*.), Advances in production management systems, Artificial intelligence for sustainable and resilient production systems. APMS 2021. IFIP Advances in information and communication technology,* Vol. 630, Springer, Cham, Switzerland, 645-655, doi: 10.1007/978-3-030-85874-2_70.
[27] Bejlegaard, M., Sarivan, I.-M., Waehrens, B.V. (2021). The influence of digital technologies on supply chain coordination strategies. *Journal of Global Operations and Strategic Sourcing,* Vol. 14, No. 4, 636-658, doi: 10.1108/jgoss-11-2019-0063.
[28] Vorkapić, M., Radovanović, F., Ćoćkalo, D., Đorđević, D. (2017). Applicability of the lean concept to the management of small-scale manufacturing enterprises in Serbia, *Tehnički vjesnik – Technical Gazette,* Vol. 24, No. 6, 1929-1934, doi: 10.17559/TV-20150807194942.