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A system dynamics archetype to mitigate rework effects in engineer-to-order supply chains

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ABSTRACT

There are established archetypes that demonstrate the dynamic properties of make-to-order/stock and assemble-to-order production planning and inventory control systems and their impact on total on-costs, allowing for performance benchmarks to be established. However, the dynamic properties of engineer-to-order (ETO) production system, where products are designed and made to a specific customer order, are not well understood. Time and cost-overrun, poor capacity planning and high rates of rework are difficulties faced by ETO managers and, for now, solutions for these problems are still lacking.

Therefore, this paper develops an ETO production model which merges a service-orientated design subsystem with a working-unit-orientated production subsystem to establish an order book-controlled ETO system. The developed model realises automatic capacity control to maintain the expected lead time and order book. At the same time, we also conduct transfer function and stability analysis on this holistic ETO model to investigate the system's dynamic properties using Control Theory and System Dynamics.

This paper's contributions could be summarised from four perspectives. 1. It provides an automatic capacity-controlled archetype for practice benchmarking and demonstrating the advantage of a whole system level order book controller. 2. The order book proportional controller, at a whole system level rather than just in the local subsystems, can offset the rework's negative impact, while achieving target order book and service times. 3. The dynamic analysis provides transfer functions, demonstrating the dynamic relationship between demand (input) with order book and lead time (outputs). 4. The derived critical condition for system stability provides guidelines for system managers to prevent the system becoming unstable.

The limitation of this paper is that we assume the rework could only happen in the production system and could be rectified in the production system. However, in practice, rework could happen and be detected everywhere. Further research could relax this assumption and explore the dynamics of these scenarios.

1. Introduction

Engineer-to-Order (ETO) supply chains are mainly adopted in 'one/first-of-kind' production environments, such as construction (Braglia et al., 2020), shipbuilding (Alfnes et al., 2021) and capital goods (Birkie et al., 2017), wherein products require a specific design to satisfy customised requirements. This feature gives ETO supply chains project characteristics and makes ETO an interdisciplinary subject that encapsulates Project Management (PM) and Supply Chain Management (SCM).

However, ETO's interdisciplinary nature, and complex interactions between design, production, and project delivery systems, increase the difficulty in model definition and positioning. Given the project delivery characteristics, a model of an ETO system should exhibit both project and supply chain features, in other words, combining aggregated level planning with project level management (Gosling et al., 2015). Therefore, an ETO archetype, which we refer to as a reference systems model typical of an ETO situation, is still little considered in current research on the dynamics of planning and control systems. This contrasts with the long history of research on the impact on the production economics, such as production on-costs and inventory variance costs, of the dynamic behaviour of make-to-order/stock (MTO/MTS) systems (see Lin et al., 2017 for a recent review) with more recent exploration of the dynamics of order-book based MTO production (Wikner et al., 2007) and assemble-to-order (ATO) systems (Lin et al., 2020). Such longevity of research builds on archetypes developed over many decades with now

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well-established performance and decision parameter benchmarks (e.g. Towill 1982; John et al., 1994; Aggelogiannaki et al., 2008; Wikner et al., 2017).

The absence of an ETO archetype motivates our research. An archetype is defined as a typical and general model of a specific system which could be used as a foundation for future study (Batista et al., 2018). A well-developed archetype may contribute by 1) providing insights into the system dynamics behaviour, providing a better theoretical understanding of ETO supply chains and 2) acting as a benchmark for future systems analysis for both academe and practice by adopting appropriate metrics.

Hence, *the aim of this paper is to develop and analyse an ETO archetype by applying system dynamics and control engineering approaches*. This translates into three objectives.

1. Determine the ETO archetype's system boundary and its positioning within the wider body of research on the dynamics of production planning and control systems (Lin et al., 2017).
2. Define and analyse distinguishing variables and features for an ETO archetype.
3. Realise an appropriate decision rule to ensure that the ETO archetype satisfies targeted system state requirements

In achieving the aim and objectives, the ETO system dynamics archetype goes beyond the traditional heartlands of production planning and control know-how. In so doing, we exploit Control Theory and System Dynamics modelling and simulation techniques that have a long and established history of application in Production Economics.

2. Theoretical background

2.1. Engineer to order system

ETO supply chains are dynamic, complex systems wherein the order penetration point is located at the design stage (Wikner and Rudberg 2005; Gosling et al., 2017). Products or services in such a system are fully driven by the customers' orders (Gosling and Naim, 2009). ETO industries have distinguishing project features, hence receiving much attention from the project management research community (Denicol et al., 2020). In contrast, much of the research on the dynamics of production planning and control systems have evolved from the SCM arena.

Aside from research that stems from the SCM field, Adrodegari et al. (2013) developed an One-of-a-Kind Production (OKP) framework, demonstrating the production process of special purpose machine industry, and highlight the critical role of Information Communication Technologies in ETO environments. Wang et al. (2016) designed a domain model of the service system, which could be used for facilitating computer assistance and human-centred decision-making. Bajomo et al. (2022) provide a SD model which simulates the material management system of the Engineering, Procurement and Construction (EPC) industry and reproduces the dynamic behaviour of material volume. Despite the forgoing, an integrated design-production aggregate planning control system which can automatically adjust capacity and absorb the impact brought by rework is still absent. At the same time, a method to analyse and explain the dynamic behaviour from a control engineering perspective is still missing.

2.2. Control theory and system dynamics applications in the ETO field

System Dynamics (SD) simulation and Control Theory are two frequently used methods in system simulation and analysis, which can be mutually transformed. Both are used in this research. Classic control theory is a widely used technique in production planning and control system dynamics research, which provides sufficient analytical tools for system dynamic analysis (Lin et al., 2017). For instance, the transfer function analysis, as the fundamental tool in control theory, provides insight to parameter value settings, transient response analysis, application of the initial- and final-value theorems and critical stability conditions. The application of control theory contributes to the Inventory Order Based Production System (IOBPCS) development (Towill 1982), regarded as the fundamental archetype for production planning and control systems (Lin et al., 2017). This method has been applied in MTO (Wikner et al., 2007), TS-MTO (Wikner et al., 2017) and ATO (Lin et al., 2020) systems.

SD is a widely used approach in both the PM and SCM fields. Adopting SD into archetype development contributes to the knowledge sharing between PM and SCM, thereby maximising the integration of PM and SCM based on SD, Peña-Mora and Li (2001) developed the Dynamic Planning Methodology for construction process analysis. This model is further adopted in change management (Lee et al., 2005; Lee and Peña-Mora 2007) and quality management (Lee et al., 2006). Moreover, Barbosa and Azevedo (2019) applied SD in MTO/ETO manufacturing environment to simulate and assess the performance of an ETO-type company.

Overall, four limitations are identified. First, the ETO SCM field partially overlaps with PM. However, the terminology in these fields has not been unified, which hinders knowledge sharing. Secondly, an aggregate-level production planning and control model for ETO, which holds a perspective from the organisational level, is still absent. The third limitation is the lack of control theory application in ETO system dynamics research, which limits research on ETO system dynamic analysis. The other limitation is modelling design and production systems is a challenging task, not many studies have modelled a design system.

3. Method

3.1. Modelling

The first step in developing an archetype is to identify and specify the key variables of ETO system, considering their unique attributes but also similarities when compared to MTS, MTO and ATO supply chains. Based on the literature reviewed in Section 2, the theoretical background provided the basis for model development from both PM and SCM perspectives. However, as the elements that constitute an ETO were established from the two disciplinary lenses, some concepts might be overlapping. Hence, we synthesis the identified variables to create a single unified archetype. The result of the background study and key variables are presented in Section 4.1.

In designing an ETO archetype there is a need to realise an appropriate control mechanism to satisfy the required system states. As Wikner et al. (2007) have shown, an order book controller has the capability to ensure a stable dynamic response of an MTO system. However, unlike a single MTO system, the ETO archetype is composed of two coupled sub-systems, therefore, there is a need to determine where the order-book controller is located. Hence, in line with Wikner et al. (2017) we adopted an experimental approach and conducted two simulations to investigate the effect of controllers at different levels, one local controller within the production sub-system, the other one being an holistic ETO system controller. Candidate models are demonstrated in block diagram form using discrete-time, z-domain, representation and via the adoption of Simulink® and difference equation simulation in Sections 4.2 and 4.3.

3.2. Simulation comparison and dynamic analysis\

After the candidate models are developed, we conduct simulations on a spreadsheet to compare their dynamic performance. Step changes are used as the input which align with previous research, and notably that of Wikner et al. (2007), to see which model could maintain lead times at a desired level. The production and design delays are both set as

1 time unit as per Chen and Disney (2007). Two scenarios are conducted with different rework ratios. Prior to the change in system input, the initial steady-state conditions for each scenario are obtained by running preliminary, warm-up simulations with a step input of 100, and with a predefined rework ratio.

With consideration of simulation accuracy and correctness, we conduct simulations for both experiments on Simulink® and by implanting difference equations in the Excel spreadsheet package. We also derived the transfer functions of both experimental models and used MATLAB® to reproduce the dynamic behaviour and compared it with the simulation results. Hence, we ensured the triangulation of results via three different techniques.

To further analyse the dynamic behaviour of the archetype we adopt the Final- and Initial-Value Theorems to study the equilibrium conditions of the models by exploiting the transfer functions. Finally, stability analysis is conducted using the Routh-Hurwitz matrix to calculate the critical stable conditions for the systems. The results are crucial for the implementation because it provides information about in what circumstances the system will become unstable. Results are given in Section 5.

4. Proposed model

4.1. Model development

The key elements identified are presented in Table 1, with the last column demonstrating the variables that will be used in model development. The reasons for consolidating are as follow:

1. Rework is a distinguishing feature of project-based production where operational excellence approaches have yet to eliminate its occurrence as often happens in manufacturing production lines.
2. We determine to model the working units rather than material flow in the system to avoid potential problems which may arise from diverse products/project properties.
3. Work rate was retained because the model in this research focuses on working units.
4. Lead time, as a key indicator for system performance and a key factor for customer satisfaction, should be included as an essential variable, used as a metric in dynamic assessment.
5. Work-to-do is merged with the order book as both represent the work waiting to be completed.

Moreover, according to the definition from Gosling and Naim (2009), ETO should consist of design and production sub-systems. Considering both the design and production sub-systems are order-driven and hold no stock, we model the two sub-systems with reference to the SCM-orientated structure of an order-book based MTO system (Wikner et al., 2007), and the structure of the Integrated Design and Operations Management (IDOM) enterprise information system that connects design with the production (Zhang et al., 2019). The synthesised archetype connects the two subsystems and models the working units at an aggregate level, providing the archetype with a PM feature. The order book, as a stock for uncompleted working units, is utilised to calculate the lead time by exploiting Little's Law (Little 1961). Moreover, we select order book and lead time as our main metrics to determine whether the system can adapt to accommodate rework or demand change while ensuring the delivery of products on time. As for rework, we need to answer two questions before going further: where does the non-conformance, that is, unqualified products or tasks, occur? And how does the system adapt to such rework?

In practice, non-conformance problems create high uncertainty, not only because they may happen at each of the design and production stages, but also because the inspection of non-conformance is often not timely (Han et al., 2013). Consequently, non-conformance detected downstream may be attributed to upstream work (Love et al., 2010). For instance, in an ETO scenario, non-conformance detected in the production system may be attributed to the design defects, which requires rework in design (Han et al., 2013). However, to focus our study, we simplify by assuming that non-conformance can only happen and be rectified in the production stage.

4.2. Experiment 1: production rework with local order book controller

Nomenclature is defined as per Table 2. Fig. 1 demonstrates the model structure of Experiment 1, in which the production sub-system rectifies non-conformances detected internally, via an inbuilt order book controller. Moreover, to ensure the controllability of the system and prevent the system from being too reactive to demand disturbances, we include a proportional controller for OB adjustment (Wikner et al., 2007),

To simplify the model and aid in the initial analysis, we make the following assumptions, commensurate with studies of previous MTO, MTS and ATO archetypes (e.g. (Towill 1982; John et al., 1994; Wikner et al., 2007; Lin et al., 2017).

1. The transfer function models developed for stocks and levels are linear and time-invariant.
2. The capacity is infinite.
3. The design and production lags are taken as a single time unit.
4. The total system lead time output calculations are based on Little's Law (Little 1961).

Table 1
Distinguishing elements of combined PM and SCM perspectives of an ETO system and synthesis result.

	Elements	Reference	Explanation	Consolidated ETO elements
Project Management	Rework	Lyneis and Ford (2007) and Love et al. (2019) Explore the impact of rework on project dynamics.	Rework is a canonical feature in project management; such a problem is often inevitable in practice.	✓
	Work-To-Do	Pena-Mora and Park (2001) and Park (2005) Study the project dynamic based on SD.	Work-To-Do is another distinguishing variable in project modelling; this variable records the overall work that has entered the system but is yet to be completed.	
	Working units	Pena-Mora and Park (2001); Lee et al. (2006) Model the working unit in their simulation.	Research in the project management field often models working units as opposed to product volume.	✓
	Work rate	Lee et al. (2005) Develop a SD model which includes work rate.	Work rates directly reflect productivity.	✓
Supply Chain Management	Order rate	Towill (1982), Lin et al. (2017), and Wikner et al. (2017). Develop supply chain models, which include order rate.	Order rate is an essential element in production planning and control, especially in order-driven systems, which determine the production speed of the supply chain.	
	Lead time	Wikner et al. (2007), Lin et al. (2020), and Spiegler et al. (2012) Study the lead time dynamic of the supply chain system.	Lead time, a vital concept in SCM, directly affects both cost and revenue, which can be used as an indicator for system performance in order-based production systems.	✓
	Order book	Wikner et al. (2007) Explore the adoption of Order Book control in MTO system.	One of the distinguishing variables in the MTO system is the order book, which represents the order waiting to be satisfied	✓

Table 2
Nomenclature.

Abbreviation	Full name	Explanation
ETO system		
DEM	Demand	Demand for the ETO system
OB	Order Book	Order Book for ETO system
LT	Lead time	The lead time of the ETO system
DELRATE	Delivery Rate	Rate of qualified products, which meet the customers' requirement
Design Sub-system		
DES	Design	Abbreviation for design
DEM_{DES}	Design Demand	Demand for the design system.
$COMRATE_{DES}$	Design Completion Rate	Completion rate of the design system
OB_{DES}	Design Order Book	Order book of the design system
LT_{DES}	lead time	The Lead time of the design system
Production Sub-system		
PROD	Production	Abbreviation for Production
DEM_{PROD}	Production Demand	Demand for the production system.
$WRATE_{PROD}$	Production work Rate	Work rate for the production system
$COMRATE_{PROD}$	Production Completion rate	Completion rate of the production system
OB_{PROD}	Production Order Book	The sum of uncompleted works (including reworks)
$RWRATE_{PROD}$	Rework rate	The number of units needing rework
LT_{PROD}	Lead time	The lead time of the production system
Coefficients		
τ_D	Expected Design Delay	Delay caused by designing or design adaptation
τ_P	Expected production Delay	Delay caused by production
τ_{OB}	Time for order book adjustment	Time used for adjusting the production system's order book
τ_{ETOOB}	Time for ETO system order book adjustment	Time used for adjusting the overall ETO order book
RW	Rework ratio	The rework ratio of the production system

5. The primary flow in the system is 'working units'; those units are homogeneous, which require the same length of time to design and produce. Therefore, the input demand for a production sub-system is equal to the completion rate of the design sub-system.
6. The workload for design and production can be measured by number of working units.
7. The system can detect non-conformance in the production stage and rectify it internally by rework.
8. The rework ratio is constant and continuous.
9. Rectifying non-conformances requires the same number of working units as the original work.

Design system:

The following formulations represent the model as given in Fig. 1. This model adopts pure delays to represent the production and design lags.

$$DEM_{DES}(t) = DEM(t) \tag{1}$$

$$COMRATE_{DES}(t) = DEM_{DES}(t - \tau_D) \tag{2}$$

This model utilises the order book to represent orders received but not yet completed and delivered to the customer.

$$OB_{DES}(t) = OB_{DES}(t-1) + DEM_{DES}(t) - COMRATE_{DES}(t) \tag{3}$$

Production system:

As per Assumption 4, the demand for production system consists of demand from the upstream system and rework from the last period.

$$DEM_{PROD}(t) = COMRATE_{DES}(t) + \ RWRATE_{PROD}\ (t-1) \tag{4}$$

Equation (1.5) represents the local order book controller mechanism. Parameter τ_{OB} is added and set to 20. This value was selected based on multiple simulation tests and chosen to ensure an overdamped system, eliminating undesirable oscillatory behaviour that will impact on capacity (Wikner et al., 2007).

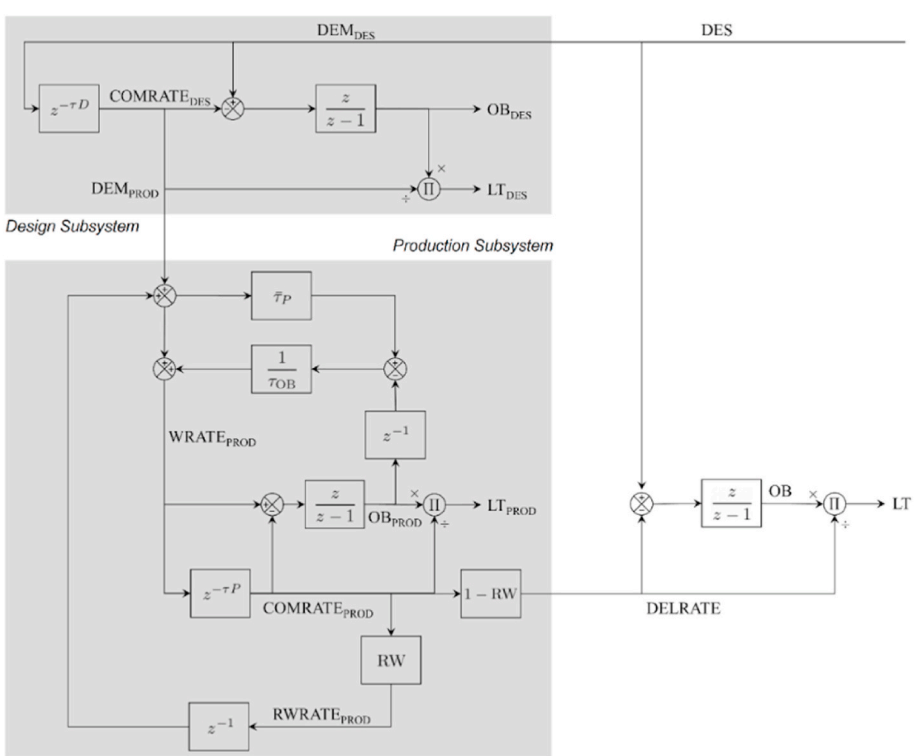

Fig. 1. Experiment 1, a candidate ETO archetype with local controller.

$$WRATE_{PROD}(t) = DEM_{PROD}(t) + \frac{OB_{PROD}(t) - DEM_{PROD}(t) \cdot \tau_P}{\tau_{OB}} \tag{5}$$

$$COMRATE_{PROD}(t) = WRATE_{PROD}(t - \tau_P) \tag{6}$$

Equation (1.7) illustrates how OB_{PROD} stores incomplete work units. We use $COMRATE_{PROD}$ instead of $DELRATE$ because $DEM_{PROD}(t)$ includes non-conformance generated working units. Therefore, the actual uncompleted working units is equal to the difference between $DEM_{PROD}(t) + RWRATE_{PROD}$ and $COMRATE_{PROD}(t)$.

$$OB_{PROD}(t) = OB_{PROD}(t-1) + DEM_{PROD}(t) - COMRATE_{PROD}(t) \tag{7}$$

RW represents the ratio of rework caused by non-conformance.

$$RWRATE_{PROD}(t) = COMRATE_{PROD}(t) \cdot RW \tag{8}$$

$$DELRATE(t) = COMRATE_{PROD}(t) \cdot (1 - RW) \tag{9}$$

$$OB(t) = OB(t-1) + DEM(t) - DELRATE(t) \tag{10}$$

We use Little's Law to calculate the delivery time.

$$LT_{DES} = \frac{OB_{DES}(t)}{COMRATE_{DES}(t)} \tag{11}$$

$$LT_{PROD} = \frac{OB_{PROD}(t)}{COMRATE_{PROD}(t)} \tag{12}$$

$$LT_{ETO} = \frac{OB(t)}{DELRATE(t)} \tag{13}$$

4.3. Experiment 2: the ETO model with holistic order book controller

Fig. 2 demonstrates the model structure for Experiment 2. The structure in the shaded box aims at keeping the overall *OB* at the desired level by adding new working units to the ETO system. This model automatically calculates the difference between the target and actual order books and sums this value with the input demand, *DEM*.

Demand for the design system is composed of the sum of input demand and a fraction of the order-book adjustment value.

Design system:

Parameter τ_{ETOOB} is a proportional controller to adjust the system response time, playing a similar role as the τ_{OB} in Experiment 1 but at a whole-systems level.

$$DEM_{DES}(t) = DEM(t) + \frac{OB(t) - DEM(t) \cdot (\tau_D + \tau_P)}{\tau_{ETOOB}} \tag{14}$$

$$COMRATE_{DES}(t) = DEM_{DES}(t - \tau_D) \tag{15}$$

$$OB_{DES}(t) = OB_{DES}(t-1) + DEM_{DES}(t) - COMRATE_{DES}(t) \tag{16}$$

Production system:

In this system the actual and target order book difference is fed back to the design system, thus for the production system, work rate is equal to the sum of new demand and rework.

$$DEM_{PROD}(t) = COMRATE_{DES}(t) + RWRATE_{PROD}(t-1) \tag{17}$$

$$WRATE_{PROD}(t) = DEM_{PROD}(t) \tag{18}$$

The other formulations of this experiment are the same as for Experiment 1 and are as given in Appendix A.

5. Experiments and results

5.1. Results of experiment 1

5.1.1. Experiment 1-local controller scenario 1: rework ratio = 0

Given the initial and coefficient values of Table 3, Fig. 3 demonstrates the transient performance of the system. The lead time of the design and production system, after an initial transient response, achieves the desired final steady-state value of 1 time unit each, with an overall ETO lead time of 2. All Order Books are doubled. Besides, the peak value for order book reach to 405 in period 7 and the peak value of lead time reaches 4 in period 6.

Table 3
Initial Value and co-efficient value for experiment 1 scenario 1, with local order book controller and rework ratio = 0.

Initial values					
$COMRATE_{DES}$	OB_{DES}	$RWRATE_{PROD}$	$COMRATE_{PROD}$	OB_{PROD}	OB
100	100	0	100	100	200
Co-efficient values					
τ_{OB}	τ_D	τ_P		*RW*	
20	1	1		0.0	

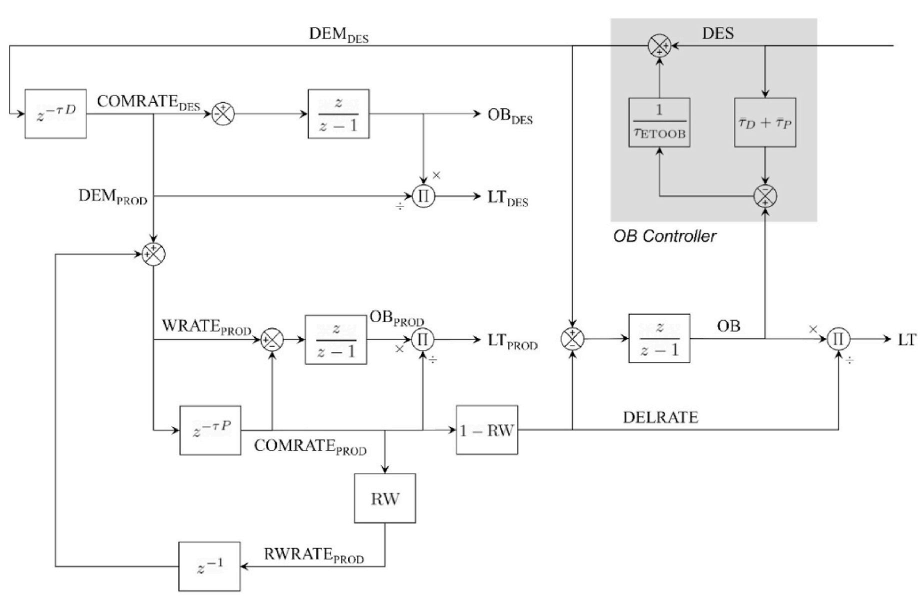

Fig. 2. Experiment 2, a candidate ETO archetype with holistic controller.

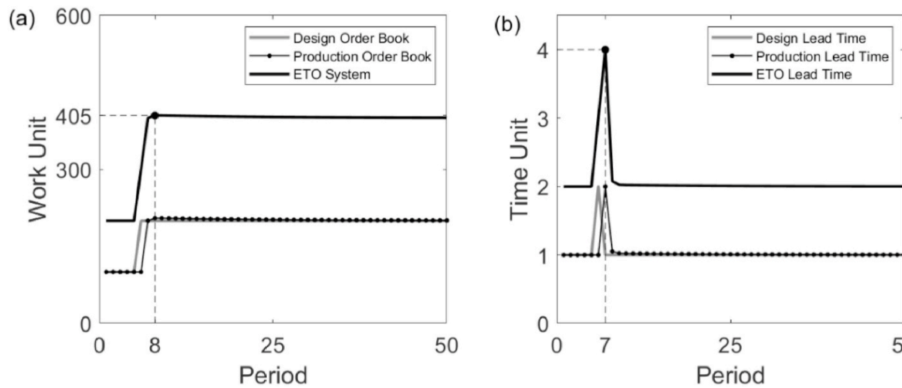

Fig. 3. Experiment 1 Scenario 1 transient state outputs, with local order book controller and rework ratio = 0.

Table 4
Initial Value and co-efficient value for experiment 1 scenario 2, with local order book controller and rework ratio = 0.2

Initial values					
$COMRATE_{DES}$	OB_{DES}	$RWRATE_{PROD}$	$COMRATE_{PROD}$	OB_{PROD}	OB
100	100	25	125	125	250
Co-efficient values					
τ_{OB}	τ_D	τ_P		RW	
20	1	1		0.2	

5.1.2. *Experiment 1-local controller—Scenario 2: rework ratio = 0.2*

To investigate the performance of the model with rework, we conducted Scenario 2, the initial values and co-efficient values are presented in Table 4. Initial values were adjusted to guarantee the system is balanced and stable at initial steady state. The initial Order Book is calculated as

$$OB_{PROD} = \tau_P \cdot \frac{DEM_{PROD}}{(1 - RW)} \tag{19}$$

In Fig. 4, the order book of the ETO system and production system stabilize at 500, which is 2.5 times of new demand. Production system order book is doubled, as calculated by equation (19). In the meantime, the lead time of the overall system is longer than $\tau_D+\tau_P$. This problem is due to gradually increased rework until the condition for balancing the rework loop given when $WRATE_{PROD}$ reach $DEM_{PROD}/(1\text{-}RW) = 125$. Such a phenomenon was also observed in Lyneis and Ford (2007)'s SD-model. Moreover, in this scenario, the peak value of lead time increased by 0.5 compared to the scenario 1, and order book peak value increased to 504, 100 units greater than Scenario 1.

According to the simulation above, the model developed in Experiment 1 does not automatically control the system to deliver products/projects on time and requires excess capacity to cope with a larger order book. Hence, we further developed this model and synthesised an order book controller at the aggregate level as given in Experiment 2.

5.2. *Results of experiment 2*

5.2.1. *Experiment 2—holistic controller – scenario 1: rework ratio = 0*

Scenario 1 aims to investigate the system performance without rework. Table 5 demonstrates the initial condition of the system. According to Fig. 5, the lead time stabilize at 2, which refers to the on-time delivery is guaranteed in long-term. Peak value of order book trace slightly increased by 10 units compared to Fig. 3.

5.2.2. *Experiment 2 – holistic controller – scenario 2: rework ratio = 0.2*

Based on scenario 1, we adjust the rework ratio to 0.2 in Table 6, and the simulation results obtained are as Fig. 6.

As shown in Fig. 6, the lead time of the overall system start at and returns to 2 time units, which is equal to the sum of production and design lead time (see Fig. 7). A similar form of response is observed in left chart of Fig. 6, the order book of the ETO system returning to 400, which is equal to $(\tau_P+\tau_D)\cdot DEM = 2\text{x}200 = 400$. However, the drawback of this model is the longer settling time although the benefits greatly outweigh this with enhanced customer due date conformance and reduced order book capacity requirements.

In summary, the model developed for Experiment 2 is capable to maintain lead time and order book at the desired levels in long term, thus, we propose this model as our ETO archetype. In Sections 5.3 and 5.4, we adopt transfer function analysis to further investigate and explain the dynamic behaviour of this archetype.

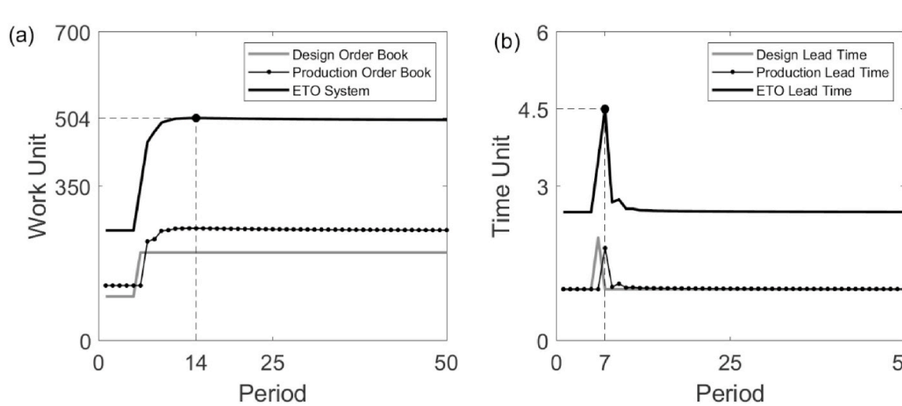

Fig. 4. Experiment 1 Scenario 2 transient state outputs, with local order book controller and rework ratio = 0.2.

Table 5
Initial Value and co-efficient value for Experiment 2 Scenario 1, with whole system level order book controller and rework ratio = 0.

Initial values					
$COMRATE_{DES}$	OB_{DES}	$RWRATE_{PROD}$	$COMRATE_{PROD}$	OB_{PROD}	OB
100	100	0	100	100	200
Co-efficient value					
τ_{ETOOB}	τ_D	τ_P		RW	
20	1	1		0.0	

5.3. *Transfer function determination and exploiting initial, final value theorems*

In this section, we deduce the transfer function for order book. Investigating this variable via the transfer function provides insight into the archetype's transient response. τ_D and τ_P are set to 1 respectively, to correspond with the simulations in Sections 5.1 and 5.2.

Using the model from Experiment 1 (localised OB control) we may derive the following transfer function.

$$F_1(z) = \frac{OB(z)}{DEM(z)} = \frac{z(2 + (-1 + z^2)\tau_{OB})}{RW(z-2) + z + (z-1)(z^2 - RW)\tau_{OB}} \tag{20}$$

and that for the ETO archetype from Experiment 2 (holistic OB control) is

$$F_2(z) = \frac{OB(z)}{DEM(z)} = \frac{z(2(1-RW) + (z^2-1)\tau_{OB})}{1 - RW + (z-1)(z^2 - RW)\tau_{OB}} \tag{21}$$

To cross-check the transfer function with simulations, we utilise the initial value theorem and final value theorem for both (20) and (21) and reproduced the dynamic behaviour in MATLAB® by visualising the transient response of equation (21), that is, for our synthesised ETO archetype.

The calculation for initial and final value theorem is as per (Truxal 1958). According to (20) and (21), following a unit step input of the form $\left(\frac{z}{z-1}\right)$, we obtain equations (22) and (23).

$$\lim_{z\to\infty}\left(F_1(z)\cdot\frac{z}{z-1}\cdot\frac{z-1}{z}\right) = 1 \quad \lim_{z\to1}\left(F_1(z)\cdot\frac{z}{z-1}\cdot\frac{z-1}{z}\right) = \frac{2}{1-RW} \tag{22}$$

$$\lim_{z\to\infty}\left(F_2(z)\cdot\frac{z}{z-1}\cdot\frac{z-1}{z}\right) = 1 \quad \lim_{z\to1}\left(F_2(z)\cdot\frac{z}{z-1}\cdot\frac{z-1}{z}\right) = 2 \tag{23}$$

In both cases the system's initial value is 1 which indicates the first increment of order book is 1 times demand. The final value for (22) is dependent on RW, which if greater than 0 will lead to an offset from the desired level. For our preferred archetypes, as per equation (23), the final is 2, which means the output is equal to the sum of designing delay and production delay. This result corresponds with Fig. 6, wherein, the sum of τ_D and τ_P is 2. Taking scaling into account, then we may determine from Fig. 6 that the first change in output value is +100 and the final value steady stat change in output is +200.

5.4. *Stability analysis*

Stability is a critical factor for the system, as an unstable system may lead to ETO failure in terms of project costs and lead time creep. Therefore, we conducted stability analysis on the ETO archetype to investigate when the system is stable and how the coefficients affect the system's stability.

To assess the stability of the model in the z-domain, we convert the characteristic equation to the ***w*** domain using the Wright function, the result is shown in (24). Then, we adopt the Routh-Hurwitz Criterion that has previously been exploited in production planning control systems (Disney and Towill 2002).

$$(1-RW)w^3 + (-3(1-RW) + 2\tau_{OB} - 2RW\tau_{ETOOB})w^2 + (3(1-RW) + 4\tau_{ETOOB} + 4RW\tau_{OB})w - 1 + RW + 2\tau_{ETOOB} - 2RW\tau_{ETOOB} \tag{24}$$

Then we can obtain the Routh array

$$\begin{array}{c|l} S^3 & 1 - RW3(1-RW) + 4\tau_{ETOOB} + 4RW\tau_{ETOOB} - 3(1-RW) + 2\tau_{ETOOB} - 2RW\tau_{ETOOB})RW - 1 + 2\tau_{ETOOB}(1-RW) \\ S^2 & \\ S^1 & \dfrac{8((RW-1) - (1-2RW)\tau_{OB} + (1+RW)\tau_{ETOOB}{}^2)}{2\tau_{ETOOB} - 3} \quad 0 \\ S^0 & (1-RW)(2\tau_{ETOOB} - 1) \end{array} \tag{25}$$

According to the Routh-Hurwitz criterion, the system is stable only when the first column of the Hurwitz matrix is all positive. RW is the

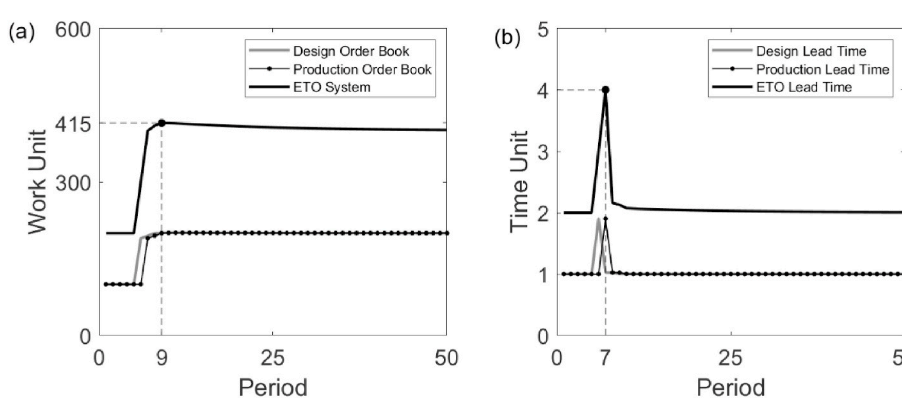

Fig. 5. Experiment 2 Scenario 1 transient state outputs, with whole system level order book controller and rework ratio = 0.

Table 6
Initial Value and co-efficient value for experiment 1 scenario 2, with whole system level order book controller and rework ratio = 0.2

Initial values					
$COMRATE_{DES}$	OB_{DES}	$RWRATE_{PROD}$	$COMRATE_{PROD}$	OB_{PROD}	OB
100	100	25	125	100	200
Co-efficient values					
τ_{ETOOB}	τ_D	τ_P		RW	
20	1	1		0.2	

rework ratio, range from 0 to 1, τ_{OB} is a proportional controller which is always greater than 1, thus the first element and the fourth element are positive. Hence, we need to assess the second and the third elements and calculate the critically stable condition. To note here, τ_{OB} is a decision parameter to be easily determined by the management team, while the rework rate is often not easy to change, hence, for equation (25), we set the necessary condition for τ_{OB}.

$$\text{Let}\begin{cases} -3(1-RW)+2\tau_{ETOOB}-2RW\tau_{ETOOB})>0 \\ \dfrac{8((RW-1)-(1-2RW)\tau_{OB}+(1+RW)\tau_{ETOOB}{}^2)}{2\tau_{ETOOB}-3}>0 \end{cases} \tag{26}$$

Then we obtain

$$\begin{cases} \tau_{ETOOB} > 1.5 \\ \textit{and} \\ \tau_{ETOOB} > \dfrac{(1-2RW)+\sqrt{5+4RW})}{2(1+RW)} \end{cases} \tag{27}$$

Therefore, the system is only stable when the parameters satisfy the formulation of Equation (27). Interestingly, when RW = 0 the critical condition is $\tau_{ETOOB} > 1.618$, the latter being the Golden Ratio, which has also been identified in previous production planning and control research (Disney et al., 2004).

To check the correctness of this result, we run the simulation, and given $\tau_P = \tau_D = 1$, RW = 0.2, step change from 100 to 200. As per (27) $\frac{(1-2RW)+\sqrt{5+4RW})}{2(1+RW)} = 1.25$, which is smaller than 1.5, thus the system is stable when $\tau_{ETOOB} > 1.5$. Thus, we test the system's dynamic when $\tau_{ETOOB} = 1.5$ *and* 1.7. The transient outputs are given in Fig. 2, where the curve of lead time and increasing peak value of order book demonstrate that the system is unstable. We also present a comparison simulation with $\tau_{OB} = 1.7$, result shows that the system converges as shown in Fig. 8.

6. Discussion

Table 7 demonstrates the theoretical contribution of this paper by comparing the proposed archetype with the previous research. From the modelling perspective, this paper contributes to the wider body of knowledge in production planning and control by providing a unique archetype for an ETO system. We introduced an order book controller into the system and discussed the effectiveness of different levels of control. We found that placing the order book controller at the whole system level maintains the lead time at the required level. The concept of order book control feedback originated a MTO system concept, presented in block-diagram form, (Wikner et al., 2007). From MTS to ETO the CODP point gradually moves upstream, hence our work sheds light on the dynamic properties of the supply chain system under the condition that CODP point locates at the design level. We also model the flow in terms of work units instead of material to include the design subsystem in our model and to accommodate diverse product/project characteristics.

For industry partitioners, this paper suggests that the order book, the sum of working units of projects or products waiting to be completed, could be used for capacity planning. However, given the unit lead times for design and productions, the capacity adjustment must be divided by τ_{OB}. Interestingly, according to Equation (27), when RW = 0, to stabilize the system, τ_{ETOOB} must be greater than 1.618, which is the golden ratio (e.g. see Disney et al., 2004). However, compared with the critical stability condition when RW = 0.2, τ_{ETOOB} must greater than 1.5, hence the boundary value for stability for the non-rework scenario is greater. However, in practice, the rework ratio is only known after the production, thus keeping τ_{ETOOB} greater than 1.618 is sufficient overall to stabilize the system. Moreover, the proposed archetype is also capable to offset the negative impact brought by rework, by preplanning extra capacity, to maintain the expected lead time. The findings from this research could benefit various industries, such as special purpose machine manufacturing, shipbuilding, and construction.

7. Conclusions

The aim of this paper is to develop and analyse an ETO archetype by applying system dynamics and control engineering approaches. The main aim is translated into three objectives.

1. Determine the ETO archetype's system boundary and its positioning within the wider body of research on the dynamics of production planning and control systems.
2. Define and analyse distinguishing variables and features for an ETO archetype.
3. Realise an appropriate decision rule to ensure the ETO archetype satisfies targeted system state requirements.

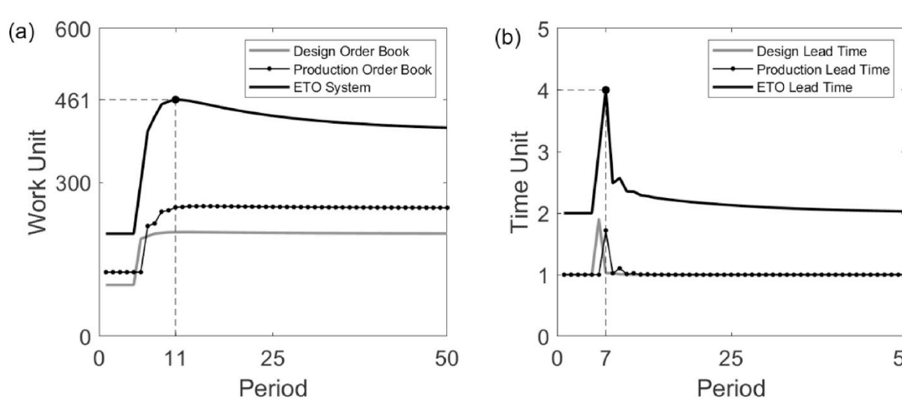

Fig. 6. Experiment 2 Scenario 2 transient state outputs, with whole system level order book controller and rework ratio = 0.2.

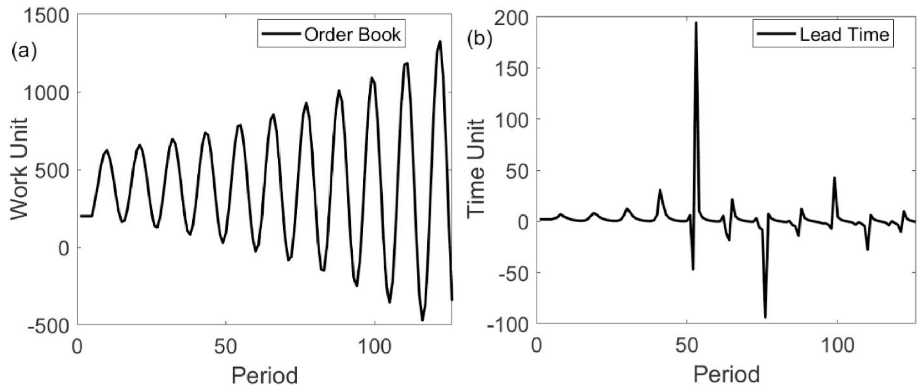

Fig. 7. Simulation result for stability analysis verification with $\tau_{ETOOB} = 1.5$.

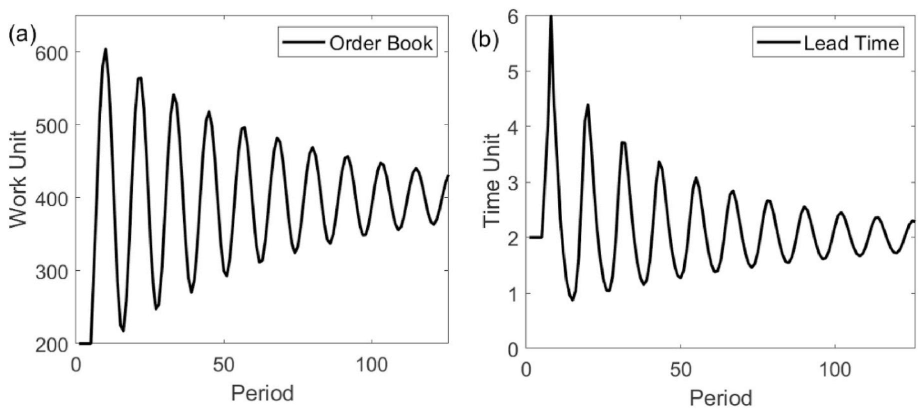

Fig. 8. Simulation result for stability analysis verification with $\tau_{ETOOB} = 1.7$.

The first two objectives are addressed in Section 4, which presents the key elements that are the distinguishing variables of ETO systems based on a theoretical background study. The third objective is addressed in Section 5. We conducted two experiments under two scenarios, and adopt transfer function analysis, Final-and Initial-value theorem, and stability analysis on the developed archetype. Finally, we develop an ETO archetype which can automatically control the production to maintain the lead time, at the same time we conclude that holistic system level order book controller is much effective than a local controller in production planning and control.

This research is limited to the assumptions listed in Section 4.2. To simplify the archetype, we assumed the capacity of both sub-systems are infinite and we determine the impact on capacity requirements by determining the variability in both order book and lead time, hence, capacity requirements may be determined. In practice however, design rework is also a great contributor to the schedule delay and cost overrun, with an even greater impact on the system. Also, the capacity is often limited, introducing nonlinear constraints to the system. Moreover, as the scope of this paper is developing the ETO archetype, we only conduct stability analysis on this system. The system's dynamic behaviour could be further explored by control theory.

Future research can focus on relaxing the assumptions listed in Section 4.2, and further develop the archetype with due consideration of design non-conformances, capacity constraints and capacity adjustment delay. Other analysis may include 1) exploiting non-linear control theory for determining the transfer function of the total system lead time variable; 2) a deeper investigation of the implication of the identification of the Golden Ratio; 3) robustness and sensitivity analyses of the system; 4) further consideration and research of the stability boundary conditions to determine the rework feedback proportional value; and 5) relaxing the assumption that the sub-system lags are of a single time unit value. Moreover, as the ETO archetype is a conceptual model, future research could adopt this archetype in practice and/or benchmark this archetype with a case study to assess the model's fidelity.

Table 7
Contribution of this paper (based on CODP considerations from Gosling et al., 2017).

System Type	*Original reference*	*Typical CODP Location*	Feedback Path	Feedforward Path	*Flow*	*Main analysis technique*
MTS	Towill (1982)	Finished stock	Inventory	Demand	Material	Laplace
ATO	Lin et al. (2017)	Sub-assembly	WIP Inventory Backlog	Demand	Material	Laplace
MTO	Wikner et al. (2007)	Raw materials	Order Book WIP	Demand	Material	Simulation
ETO	This paper	Design	Order Book	Demand	Work Unit	z-transform

Declaration of competing interest

None.

Data availability

No data was used for the research described in the article.

Appendix A. Experiment 2, holistic order book controller, mathematical formulations

Design system

$$DEM_{DES}(t) = DEM(t) + \frac{OB(t) - DEM(t)\cdot(\tau_D + \tau_P)}{\tau_{ETOOB}} \tag{A.1}$$

$$COMRATE_{DES}(t) = DEM_{DES}(t - \tau_D) \tag{A.2}$$

$$OB_{DES}(t) = OB_{DES}(t-1) + DEM_{DES}(t) - COMRATE_{DES}(t)\#(A.3) \tag{A.3}$$

Production system

$$DEM_{PROD}(t) = COMRATE_{DES}(t) + RWRATE_{PROD}(t-1) \tag{A.4}$$

$$WRATE_{PROD}(t) = DEM_{PROD}(t) \tag{A.5}$$

$$COMRATE_{PROD}(t) = WRATE_{PROD}(t - \tau_P) \tag{A.6}$$

$$OB_{PROD}(t) = OB_{PROD}(t-1) + DEM_{PROD}(t) - COMRATE_{PROD}(t) \tag{A.7}$$

$$RWRATE_{PROD}(t) = COMRATE_{PROD}(t)\cdot RW \tag{A.8}$$

$$DELRATE(t) = COMRATE_{PROD}(t)\cdot(1 - RW) \tag{A.9}$$

$$OB(t) = OB(t-1) + DEM(t) - DELRATE(t) \tag{A.10}$$

$$LT_{DES} = \frac{OB_{DES}(t)}{COMRATE_{DES}(t)} \tag{A.11}$$

$$LT_{PROD} = \frac{OB_{PROD}(t)}{COMRATE_{PROD}(t)} \tag{A.12}$$

$$LT_{ETO} = \frac{OB(t)}{DELRATE(t)} \tag{A.13}$$

References

Adrodegari, F., Bacchetti, A., Sicco, A., Pirola, F., Pinto, R., 2013. One-of-a-Kind Production (OKP) planning and control: an empirical framework for the special purpose machines industry. IFIP Adv. Inf. Commun. Technol. 398 (PART 2), 630–637. https://doi.org/10.1007/978-3-642-40361-3_80.

Aggelogiannaki, E., Doganis, P., Sarimveis, H., 2008. An adaptive model predictive control configuration for production-inventory systems. Int. J. Prod. Econ. 114 (1), 165–178. https://doi.org/10.1016/j.ijpe.2008.01.003.

Alfnes, E., Gosling, J., Naim, M., Dreyer, H.C., 2021. Exploring systemic factors creating uncertainty in complex engineer-to-order supply chains: case studies from Norwegian shipbuilding first tier suppliers. Int. J. Prod. Econ. 240 (June 2020), 108211 https://doi.org/10.1016/j.ijpe.2021.108211. Available at:

Bajomo, M., Ogbeyemi, A., Zhang, W., 2022. A systems dynamics approach to the management of material procurement for Engineering, Procurement and Construction industry. Int. J. Prod. Econ. 244 (July 2021), 108390 https://doi.org/10.1016/j.ijpe.2021.108390. Available at:

Barbosa, C., Azevedo, A., 2019. Assessing the impact of performance determinants in complex MTO/ETO supply chains through an extended hybrid modelling approach. Int. J. Prod. Res. 57 (11), 3577–3597. https://doi.org/10.1080/00207543.2018.1543970. Available at:

Batista, L., Bourlakis, M., Smart, P., Maull, R., 2018. In search of a circular supply chain archetype–a content-analysis-based literature review. Prod. Plann. Control 29 (6), 438–451. https://doi.org/10.1080/09537287.2017.1343502. Available at:

Birkie, S.E., Trucco, P., Kaulio, M., 2017. Sustaining performance under operational turbulence: the role of Lean in engineer-to-order operations. International Journal of Lean Six Sigma 8 (4), 457–481. https://doi.org/10.1108/IJLSS-12-2016-0077.

Braglia, M., Dallasega, P., Marrazzini, L., 2020. Overall Construction Productivity: a new lean metric to identify construction losses and analyse their causes in Engineer-to-Order construction supply chains. Prod. Plann. Control 1–18. https://doi.org/10.1080/09537287.2020.1837931, 0(0) Available at:

Chen, Y.F., Disney, S.M., 2007. The myopic order-up-to policy with a proportional feedback controller. Int. J. Prod. Res. 45 (2), 351–368. https://doi.org/10.1080/00207540600579532.

Denicol, J., Davies, A., Krystallis, I., 2020. What are the causes and cures of poor megaproject performance? A systematic literature review and research agenda. Proj. Manag. J. 51 (3), 328–345. https://doi.org/10.1177/8756972819896113.

Disney, S.M., Towill, D.R., 2002. A discrete transfer function model to determine the dynamic stability of a vendor managed inventory supply chain. Int. J. Prod. Res. 40 (1), 179–204. https://doi.org/10.1080/00207540110072975.

Disney, S.M., Towill, D.R., Van De Velde, W., 2004. Variance amplification and the golden ratio in production and inventory control. Int. J. Prod. Econ. 90 (3), 295–309. https://doi.org/10.1016/j.ijpe.2003.10.009.

Gosling, J., Hewlett, B., Naim, M.M., 2017. Extending customer order penetration concepts to engineering designs. Int. J. Oper. Prod. Manag. 37 (4), 402–422. https://doi.org/10.1108/IJOPM-07-2015-0453.

Gosling, J., Naim, M.M., 2009. Engineer-to-order supply chain management: a literature review and research agenda. Int. J. Prod. Econ. 122 (2), 741–754. https://doi.org/10.1016/j.ijpe.2009.07.002. Available at:

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. Prod. Plann. Control 26 (3), 203–218. https://doi.org/10.1080/09537287.2014.880816. Available at:

Han, S., Love, P., Peña-Mora, F., 2013. A system dynamics model for assessing the impacts of design errors in construction projects. Math. Comput. Model. 57 (9–10), 2044–2053. https://doi.org/10.1016/j.mcm.2011.06.039. Available at:
John, S., Naim, M.M., Towill, D.R., 1994. Dynamic analysis of a WIP compensated decision support system. Int. J. Manuf. Syst. Des. 1 (4), 283–297.
Lee, S., Peña-Mora, F., Park, M., 2005. Quality and change management model for large scale concurrent design and construction projects. J. Construct. Eng. Manag. 131 (8), 890–902. https://doi.org/10.1061/(ASCE)0733-9364(2005)131:8(890). Available at:
Lee, S., Peña-Mora, F., Park, M., 2006. Web-enabled system dynamics model for error and change management on concurrent design and construction projects. J. Comput. Civ. Eng. 20 (4), 290–300. https://doi.org/10.1061/(ASCE)0887-3801(2006)20:4(290). Available at:
Lee, S.H., Peña-Mora, F., 2007. Understanding and managing iterative error and change cycles in construction. Syst. Dynam. Rev. 23 (1), 35–60. https://doi.org/10.1002/sdr.359.
Lin, J., Naim, M.M., Purvis, L., Gosling, J., 2017. The extension and exploitation of the inventory and order based production control system archetype from 1982 to 2015. Int. J. Prod. Econ. 194 (April 2016), 135–152. https://doi.org/10.1016/j.ijpe.2016.12.003. Available at:
Lin, J., Naim, M.M., Spiegler, V.L.M., 2020. Delivery time dynamics in an assemble-to-order inventory and order based production control system. Int. J. Prod. Econ. 223 (August 2019), 107531 https://doi.org/10.1016/j.ijpe.2019.107531. Available at:
Little, J.D.C., 1961. A proof for the queuing formula: $l = \lambda W$. Oper. Res. 9 (3), 383–387. https://doi.org/10.1287/opre.9.3.383.
Love, P.E.D., Mandal, P., Li, H., 2010. Determining the Causal Structure of Rework Influences in Construction Determining the Causal Structure of Rework Influences in Construction, p. 6193. https://doi.org/10.1080/014461999371420.
Love, P.E.D., Smith, J., Ackermann, F., Irani, Z., 2019. Making sense of rework and its unintended consequence in projects : the emergence of uncomfortable knowledge. Int. J. Proj. Manag. 37 (3), 501–516. https://doi.org/10.1016/j.ijproman.2019.02.004. Available at:
Lyneis, J.M., Ford, D.N., 2007. System dynamics applied to project management: a survey, assessment, and directions for future research. Syst. Dynam. Rev. 23 (2–3), 157–189. https://doi.org/10.1002/sdr.377. Available at:
Park, M., 2005. Model-based dynamic resource management for construction projects. Autom. ConStruct. 14 (5), 585–598. https://doi.org/10.1016/j.autcon.2004.11.001. Available at:
Peña-Mora, F., Li, M., 2001. Dynamic planning and control methodology for design/build fast-track construction projects. J. Construct. Eng. Manag. 127 (1), 1–17. https://doi.org/10.1061/(ASCE)0733-9364(2001)127:1(1). Available at:
Pena-Mora, F., Park, M., 2001. Dynamic planning for fast-tracking building construction projects. J. Construct. Eng. Manag. 127 (6), 445–456. https://doi.org/10.1061/(ASCE)0733-9364(2001)127:6(445). Available at:
Spiegler, V.L.M., Naim, M.M., Wikner, J., 2012. A control engineering approach to the assessment of supply chain resilience. Int. J. Prod. Res. 50 (21), 6162–6187. https://doi.org/10.1080/00207543.2012.710764.
Towill, D.R., 1982. Dynamic analysis of an inventory and order based production control system. Int. J. Prod. Res. 20 (6), 671–687. Available at: http://www.tandfonline.com/doi/abs/10.1080/00207548208947797.
Truxal, J.G., 1958. Control Engineers' Handbook, first ed. McGraw-Hill, New York.
Wang, J.W., Wang, H.F., Ding, J.L., Furuta, K., Kanno, T., Ip, W.H., Zhang, W.J., 2016. On domain modelling of the service system with its application to enterprise information systems. Enterprise Inf. Syst. 10 (1), 1–16. https://doi.org/10.1080/17517575.2013.810784.
Wikner, J., Naim, M.M., Rudberg, M., 2007. Exploiting the order book for mass customized manufacturing control systems with capacity limitations. IEEE Trans. Eng. Manag. 54 (1), 145–155. https://doi.org/10.1109/TEM.2006.889073.
Wikner, J., Naim, M.M., Spiegler, V.L.M., Lin, J., 2017. IOBPCS based models and decoupling thinking. Int. J. Prod. Econ. 194 (April 2016), 153–166. https://doi.org/10.1016/j.ijpe.2017.05.009. Available at:
Wikner, J., Rudberg, M., 2005. Integrating production and engineering perspectives on the customer order decoupling point. Int. J. Oper. Prod. Manag. 25 (7), 623–641. https://doi.org/10.1108/01443570510605072.
Zhang, W.J., Wang, J.W., Lin, Y., 2019. Integrated design and operation management for enterprise systems. Enterprise Inf. Syst. 13 (4), 424–429. https://doi.org/10.1080/17517575.2019.1597169. Available at:

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