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# An information-centric framework for sales and operations planning in engineer-to-order manufacturing: evidence from four industrial cases

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## ABSTRACT

Traditional sales and operations planning (S&OP) frameworks, designed for stable products and predictable demand, are not well-suited to engineer-to-order (ETO) manufacturing with its extreme customisation, project-based work, and complex interdependencies. ETO environments face two challenges: epistemic uncertainty (unknown final requirements) and equivocality (conflicting interpretations of available information). Using organisational information processing theory (OIPT) and planning quality, we explore how these challenges create unique information processing requirements (IPRs) that demand an adaptive S&OP process. In a multiple-case study of four ETO manufacturers, our analysis reveals sources of these challenges (9 uncertainty and 16 equivocality drivers) and persistent mismatches between IPRs and existing information processing capacity (IPC), especially related to order-size impact analysis, specification management, and resource allocation. These findings inform an IPC-building framework comprising 52 strategies that shift the focus from process standardisation to the development of adaptive S&OP capabilities. The framework emphasises organisational prerequisites (e.g. learning culture) and digital technologies.

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## KEYWORDS

Sales and operations planning; engineer-to-order; organisational information processing theory; equivocality; planning quality

## 1. Introduction



Engineer-to-order (ETO) manufacturers face substantial uncertainty due to extensive product and process customisation (Alfnes et al. 2021). This unique and variable demand complicates coordination with supply capacity. Therefore, ETO systems need adaptive tactical demand–supply balancing processes, like sales and operations planning (S&OP) (Shurrab, Jonsson, and Johansson 2022b). However, traditional S&OP approaches are suited for standardised environments, such as configure-to-order (CTO) and make-to-stock (MTS) (Bhalla, Alfnes, and Hvolby 2023a), where demand features predefined product requirements and fulfilment processes are stable (Olhager 2010). The dynamic ETO environment poses distinct planning challenges, including uncertain specifications, frequent design modifications, continuous customer involvement, and interdependent project schedules (Bhalla et al. 2023b).


Two aspects distinguish ETO environments. One is that customer requirements evolve throughout the project lifecycle. ETO systems fulfil individual customer orders through dedicated projects, and information about customer order requirements across concurrent projects matures through ongoing interactions with customers and suppliers (Shurrab, Jonsson, and Johansson 2022a). This progressive revelation of information compels continuous adaptation (Cannas et al. 2020).

The other distinction is that engineering capacity is often an operational bottleneck (Hans et al. 2007). Unlike their traditional role in standardised operations, which is limited to research and development (R&D) activities, engineers in ETO systems are utilised for both R&D and order fulfilment (Shurrab, Jonsson, and Johansson 2022a). This high demand for engineers in ETO systems cannot be sufficiently resolved by hiring many engineers, as they are costly and multifaceted, meaning any slight excess in their capacity can quickly erode project profitability (Olhager 2010). Furthermore, hiring new engineers (or letting go of existing ones) to meet changing demand involves lengthy and often unpredictable learning curves that introduce uncertainty about contributions (Shurrab, Jonsson, and Johansson 2022b).

S&OP is meant to manage medium-term dynamics (Kristensen and Jonsson 2018), yet its application in the ETO landscape of uncertainty and equivocality requires deeper empirical study (Bhalla, Alfnes, and Hvolby 2023a; Bhalla et al. 2023b). We employ a multiple-case study method, grounded in organisational information processing theory (OIPT) (Galbraith 1977), to explore how these challenges manifest in S&OP settings and to identify effective management strategies.

Our contribution is threefold. First, we use OIPT to conceptualise ETO sources of uncertainty and equivocality, to operationalise planning quality (Oliva and Watson 2011) as a

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diagnostic instrument, and to sharpen the discourse on S&OP design-environment relationships (e.g. Kreuter et al. 2021; 2022; Pereira, Oliveira, and Carravilla 2020). Second, we develop a framework of actionable strategies that practitioners can deploy to build adaptive capability in ETO S&OP. Third, we establish an information-category-level account of ETO S&OP that locates where uncertainty and equivocality manifest within specific decision domains, complementing process-design-level theorisation of S&OP in ETO environments (Shurrab and Jonsson 2026).

## 2. Literature review

### 2.1. OIPT foundations for managing uncertainty and equivocality

OIPT establishes that effective decision-making depends on the alignment of a firm's information processing capacity (IPC) with its information processing requirements (IPRs) (Galbraith 1977). This alignment, or 'fit', affects organisational performance (Venkatraman 1989) and is achieved through mechanisms such as creating slack resources, establishing self-contained tasks, implementing information systems, and developing lateral relationships (Galbraith 1977).

IPRs are fundamentally shaped by *uncertainty* (i.e. a lack of information) and *equivocality* (i.e. multiple conflicting interpretations of available information) (Daft and Lengel 1986). Uncertainty is reduced by gathering more data, while resolving equivocality requires aligning stakeholder perspectives (Bensaou and Venkatraman 1995). Weick's (1979) sense-making perspective shows how human interactions reduce both states through continuous interpretation and meaning-making. This framing positions organisations as dynamic evolving entities. Reducing equivocality specifically depends on synchronising the richness of communication media with the message's ambiguity (Rice 1992), as different communication types (i.e. verbal, written, and nonverbal) vary in their effectiveness depending on the complexity and the ambiguity of the information (Daft and Lengel 1986).

The choice of OIPT for this study is due to demand-supply balancing (integration) being inherently information-centric and requiring intensive information processing across organisational layers (Schlegel, Birkel Hendrik, and Hartmann 2021). Accordingly, effective S&OP generates sufficient IPC to meet the IPRs driven by environmental uncertainty and equivocality.

Existing OIPT research explores mechanisms for managing these challenges (Aben et al. 2021; Bensaou and Venkatraman 1995; Daft and Macintosh 1981; Foerstl, Meinschmidt, and Busse 2018; Galbraith 1977), and S&OP studies draw parallels with coordination mechanisms to guide planning (e.g. Goh and Eldridge 2015; Oliva and Watson 2011; Tuomikangas and Kaipia 2014). However, the literature often falls short in the ETO context (Bhalla et al. 2023b; Kristensen and Jonsson 2018). Research outside S&OP, in project and supply chain management, offers relevant insights for navigating the planning complexities in ETO environments. This work distinguishes between predictable, unpredictable (e.g. Simchi-Levi et al. 2015), known, and

unknown uncertainties (e.g. Ramasesh and Browning 2014; Sengupta et al. 2025), which can take various operational forms in ETO (for instance, evolving design specifications that cause continuous changes during delivery) (Kaut, Vaagen, and Wallace 2021). Here, the gap in knowledge can range from foreseeable variations to chaos wherein project goals become unstable (De Meyer, Loch, and Pich 2002); for example, uncertainty in the product design itself typically causes changes throughout the project delivery (Kaut, Vaagen, and Wallace 2021). Consequently, ETO planning must be flexible and adaptive, rather than focused on troubleshooting (Pich, Loch, and Meyer 2002).

Examples of mechanisms to manage uncertainty in ETO environments include: incorporating design flexibility, so as to understand and model where and when to develop buffers and flexibilities (Vaagen, Kaut, and Wallace 2017); analysing scenarios and codifying learning from past problems, to inform future planning and predefine actions (Ramasesh and Browning 2014); and monitoring and assessing weak signals in order to pre-empt problems (Simchi-Levi et al. 2015). Although this literature does not focus on S&OP, its proposed capabilities inform how an adaptive S&OP can distinguish between different types of uncertainties.

### 2.2. Planning complexities in ETO environments

Planning ETO operations is information-intensive, due to unique contextual complexities that impose conditions of uncertainty and equivocality (Shurrab, Jonsson, and Johansson 2022b). These characteristics, detailed in Table 1, generate distinct IPRs. For one, uncertainty about final product specifications calls for iterative engineering processes (Benjaminsen and Sørnes 2026); thus, S&OP needs to accommodate multiple revision cycles and their associated costs unless the process has built-in flexibility. In addition, equivocality in customer requirements demands extensive coordination to facilitate richer information exchanges and to forge a joint interpretation. Understanding this relationship between ETO complexities and the IPRs they create provides the foundation for developing more effective S&OP processes.

### 2.3. ETO uncertainty and equivocality

Uncertainty and equivocality often coexist within ETO projects and systems (Shurrab, Jonsson, and Johansson 2022b, 2022a). The dominant form of uncertainty specific to this environment can be understood as epistemic (Benjaminsen and Sørnes 2026), entailing the fundamental lack of knowledge (that, in theory, is possible to gain) about the project's final state (Packard and Clark 2020; Sengupta et al. 2025). This uncertainty primarily originates from demand, technical, and resource factors. Unpredictable customer orders and varying customisation requirements create demand uncertainty, as traditional forecasting fails (Shurrab, Jonsson, and Johansson 2022a); technical uncertainty emerges from complex engineering processes and evolving design requirements (Gosling, Hewlett, and Naim 2017); and resource

**Table 1.** Planning complexities in ETO environments.

ETO characteristic	Complexity	Source (example)
Concurrent engineering and production	Resource allocation, capacity planning, and operational coordination across multiple projects are complex.	Cannas et al. (2019)
Varying customer involvement	Need to accommodate changing customer requirements and approvals throughout order fulfilment.	Shurrab, Jonsson, and Johansson (2022a)
Balancing standardisation and customisation	Must balance the efficiency of standardisation with the need for project-specific customisation.	Gosling, Hewlett, and Naim (2017)
Progressive information revelation	Incomplete information at initial planning stages; specifications evolve throughout the project lifecycle.	Alfnes et al. (2021)
Engineering and production interdependencies	Multiple iterative cycles of research, development, and specification refinement need to be synchronised with production.	Shurrab, Jonsson, and Johansson (2022b)
Resource multi-dimensional flexibility requirement	Engineering resources must handle varying design complexity; production resources must accommodate different product configurations.	Carvalho, Oliveira, and Scavarda (2015)
Project portfolio complexity	Simultaneous management of multiple projects with unique requirements and varying stages of completion.	Hans et al. (2007)

uncertainty is related to variable capacity requirements and the availability of specialised skills (Carvalho, Oliveira, and Scavarda 2015).

ETO equivocality primarily originates from ambiguous customer requirements and complex technical specifications. For the former, customers typically provide broad and loosely defined expectations, which leaves room for differing interpretations among engineers, project managers, and procurement teams (Alfnes et al. 2021). These initial ambiguities cascade across the project lifecycle, as stakeholders draw on their own assumptions to fill information gaps, which leads to inconsistent decisions, conflicting priorities, and delays in execution (Shurrab, Jonsson, and Johansson 2022b). For the latter, translating high-level customer requirements is rarely straightforward (Arica, Bakaas, and Sriram 2020) and can lead to misunderstandings about performance criteria, system interfaces, and quality standards (Nardelli et al. 2019). When specifications involve interdependent technical components across multiple domains, alignment becomes even more challenging, as each domain may apply different assumptions to the same set of instructions (Willner et al. 2016). This ongoing cycle of (re)interpretation perpetuates ambiguity (Shurrab, Jonsson, and Johansson 2022a).

ETO uncertainty and equivocality are linked in a self-reinforcing cycle. The epistemic uncertainty from an undefined project scope calls for preliminary information. This information is inherently ambiguous and, in turn, becomes a source of equivocality when different functional groups develop conflicting interpretations. Decisions taken based on divergent understandings can then lead to rework and to unforeseen integration problems. As an example, when engineering teams design components based on differing assumptions about technical specifications, the resulting integration failures create uncertainties about project timelines, costs, and resource availability. In other words, the rework cycle transforms the initial lack of knowledge into concrete project disruptions.

#### 2.4. ETO S&OP performance

S&OP offers a structured approach to integrating demand and supply. In ETO environments, its effectiveness depends on how well organisations manage the transfer and

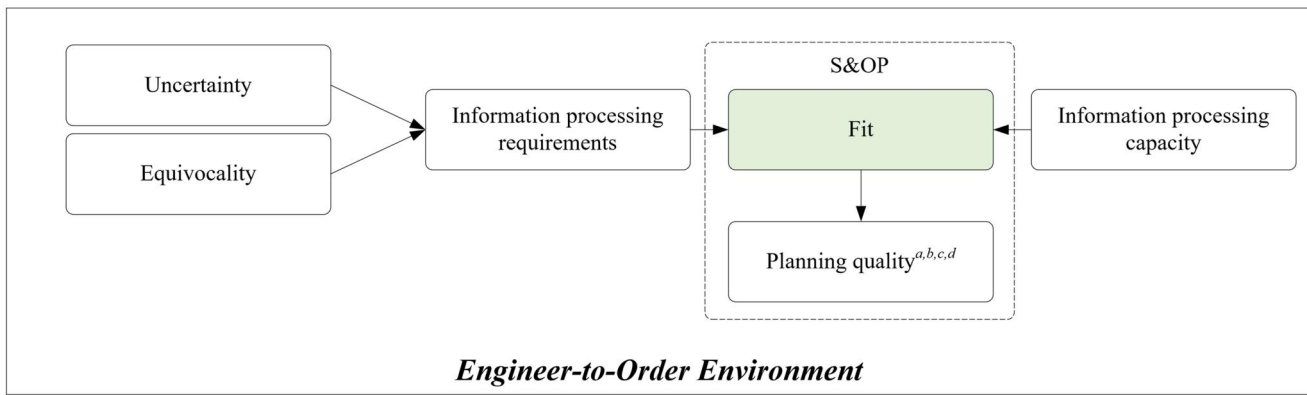
translation of information between project phases and across functional domains (Shurrab, Jonsson, and Johansson 2022b).

Recent systematic literature reviews have advanced the understanding of S&OP in ETO in terms of setting delivery dates (Bhalla et al. 2023b) as well as practices for balancing engineering capacity, procurement timelines, and production workloads (Bhalla, Alfnes, and Hvolby 2023a). Schlegel, Birkel Hendrik, and Hartmann (2021) were the first to adopt the OIPT lens to study S&OP, but since ETO per se is not addressed, their work does not capture essential issues associated with, e.g. the characteristics of steep unpredictable learning curves and engineering-centric project execution. The same applies to other S&OP studies that examine cross-functional coordination mechanisms (e.g. Goh and Eldridge 2024; Tuomikangas and Kaipia 2014).

Successful S&OP implementation entails generating IPC that fulfils the IPRs inherent in the uncertainty and equivocality landscape. This alignment corresponds to installing adaptive supply chain planning strategies (Sengupta et al. 2025), particularly adaptive capabilities for managing project uncertainties (e.g. De Meyer, Loch, and Pich 2002; Kaut, Vaagen, and Wallace 2021; Ramasesh and Browning 2014; Vaagen, Kaut, and Wallace 2017). However, measurement of the effectiveness of such strategies lacks theoretical support. Existing S&OP maturity frameworks (e.g. Danese, Molinaro, and Romano 2018; Grimson and Pyke 2007) are often criticised for measuring the adoption of practices rather than their suitability for the underlying context (Kristensen and Jonsson 2018). Moreover, conventional metrics also prove insufficient for measuring the impact of uncertainty and equivocality on S&OP requirements (Hulthén, Näslund, and Norrman 2016), an inadequacy that is magnified in ETO operations. Thus, indirect indicators are needed.

#### 2.5. S&OP quality

Building on OIPT principles and ETO-specific complexities, we propose S&OP quality as a measure for assessing S&OP's information-processing performance through the IPR-IPC fit lens. Accordingly, we adopt four quality dimensions from Oliva and Watson (2011), which we extend to address ETO-specific complexities (see Figure 1).



<sup>b</sup>**Procedural Quality:** Ability to develop and apply appropriate methods to identify, measure, and manage uncertainty and equivocality.

<sup>c</sup>**Alignment Quality:** Ability to facilitate effective communication about uncertainty and equivocality between departments and ensure that constraints and dependencies are properly understood and considered in planning processes.

<sup>a</sup>**Informational Quality:** Ability to collect, organize, and present information in formats that support effective decision-making.

<sup>d</sup>**Constructive Engagement:** Ability to mobilize and integrate diverse expertise before key decision points, ensuring that technical insights and practical constraints are properly considered in planning processes.

Figure 1. Conceptual framework.

We posit that two dimensions—informational quality (IQ) and procedural quality (PQ)—are more closely associated with S&OP's technical side. IQ represents the process ability to collect, organise, and present documented and tacit information from various sources in formats that support effective decision-making throughout projects' lifecycles. Consequently, IQ helps in managing the evolution of initial customer requirements towards detailed engineering specifications in ETO environments. PQ is conceptualised as S&OP's ability to develop and apply the appropriate methods to identify, measure, and manage uncertainty and equivocality when working with preliminary specifications and evolving customer requirements. In other words, PQ affects the choice of the planning and delivery approach and thus holds the potential to enable adaptability in ETO operations and projects, especially during the initial planning stages, which are characterised by incomplete, vague, and conflicting information (Alfnes et al. 2021).

The other two dimensions—alignment quality (AQ) and constructive engagement (CE)—are located on S&OP's social side. AQ represents the process ability to facilitate effective communication about uncertainty and equivocality between departments and to ensure that constraints and dependencies are adequately understood and considered in planning processes. Thus, this ability supports making decisions in ETO S&OP that are characterised by complex ramifications across engineering, production, and customer interfaces. Finally, CE is understood as S&OP's ability to mobilise and integrate diverse expertise before decision points, to ensure that technical insights and practical constraints are comprehensively considered in planning processes. Accordingly, this ability supports the distribution of necessary ETO knowledge across multiple technical specialists and project teams.

Figure 1 illustrates the framing of these four dimensions with other central concepts to provide a structured evaluation method that goes beyond traditional metrics and offer insights into developing the required IPC. The dimensions

reveal fit and lack-of-fit configurations between IPRs and IPC. Fit configurations indicate that IPC-building strategies are fulfilling planning quality, while lack-of-fit configurations identify shortfalls in planning quality that specific IPC-building strategies can address.

### 3. Research methodology

#### 3.1. Research process design

We used a multiple-case study approach to explore how ETO uncertainty and equivocality manifest in S&OP settings and to identify the IPC generated by S&OP; this approach is well-suited for in-depth investigations of 'how' and 'why' questions (Yin 2017). S&OP literature lacks context-dependent frameworks (Kreuter et al. 2021), which are needed as a basis for operationalising OIPT in this study. Case studies can address such a limitation through multi-source data collection, which allows for triangulation (Voss, Tsikriktsis, and Frohlich 2002), higher validity, and construct development (Eisenhardt 1989). Our systematic process established clear analytical pathways from empirical observations to theoretical constructs. Figure 2 presents the research steps, which are further described in the following sections.

#### 3.2. Case selection

We selected large (EU recommendation 2003/361), ETO-focused, international manufacturers with established S&OP to narrow the scope, improve the homogeneity, and control for population variations (Eisenhardt 1989). Such firms are among the few that have managed to implement S&OP in ETO environments (see Laari et al. 2023), meaning they offer revelatory insights (Yin 2017).

Large manufacturers were chosen because ETO tactical planning requires substantial organisational capabilities (Bhalla et al. 2023b), especially in information processing and

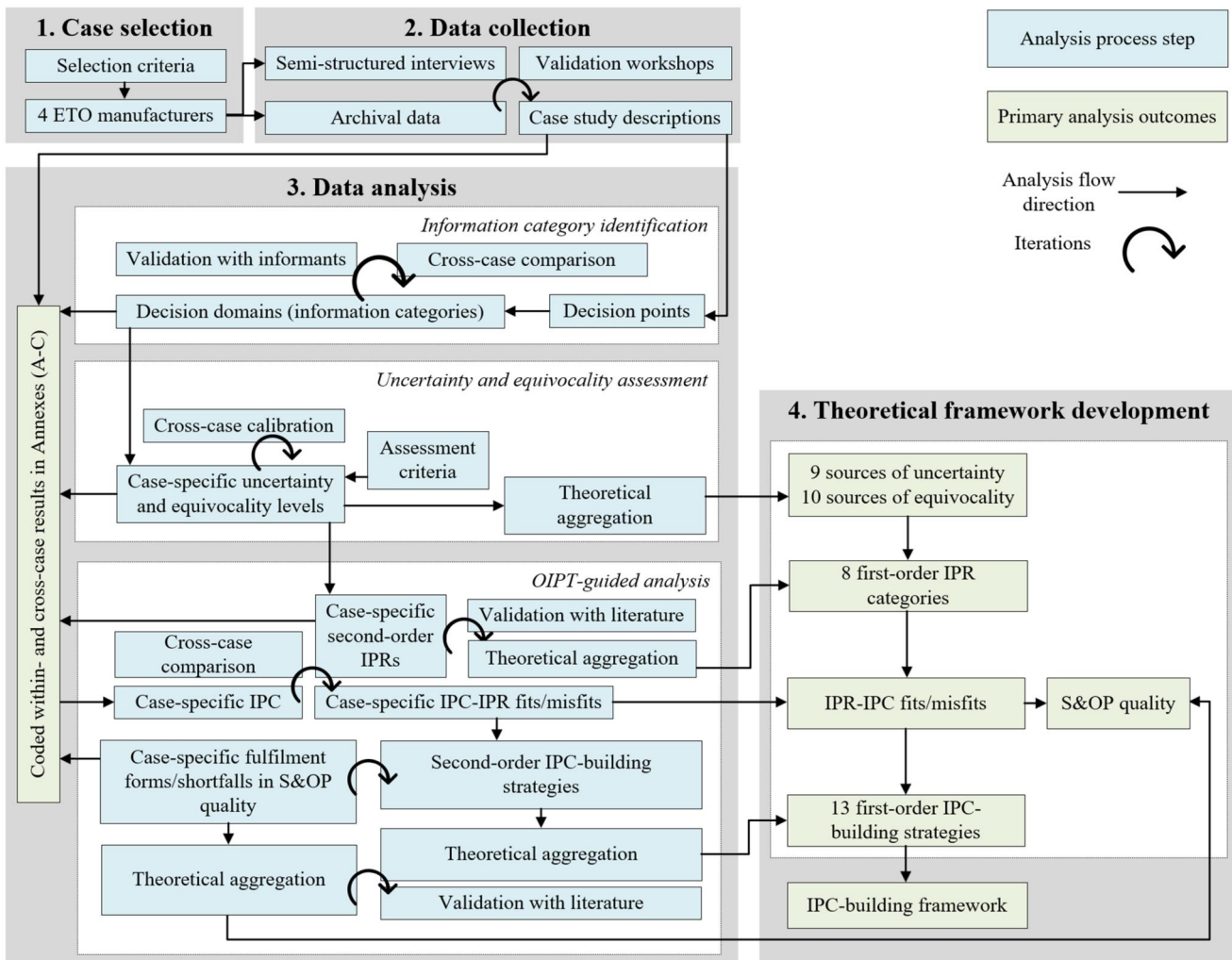


Figure 2. Research process steps.

cross-functional integration (Shurrab, Jonsson, and Johansson 2022a). The resources and formalised processes of such firms thus provide a rich context for examining mature S&OP practices (e.g. Wallace and Stahl 2008). In addition, we specifically targeted high-performing firms in their respective industries, hypothesising that managers in such organisations could more comprehensively articulate the varying degrees of uncertainty and equivocality across different decision domains (Prajogo et al. 2018).

To ensure the transferability of our findings, the final selection included firms from four industries, all of which face pressure from frequent engineering changes (see Table 2). This variety provided a firsthand view of ETO-specific challenges. The cross-case diversity in decoupling strategies and in S&OP maturity also supports theoretical replication (Eisenhardt 1989). Table 3 presents the overall S&OP decision domains for each company, providing contextual grounding for examining the manifestation of uncertainty and equivocality within their established planning frameworks.

The empirical base reported here also supports a separate study (Shurrab and Jonsson 2026) conducted within the same research program. Both studies empirically analyse the

same case companies, but they address different research questions and different units of analysis.

### 3.3. Data collection

We used a case study protocol (see Table A1) to develop in-depth descriptions of each case's S&OP environment, which is our unit of analysis. For triangulation (Voss, Tsiriktsis, and Frohlich 2002), we collected data from semi-structured interviews, archival documents, and workshops.

The semi-structured interviews investigated how ETO-specific uncertainty and equivocality arose in decision domains, which we label 'information categories'. To prevent hindsight bias and/or confirmation bias (Leonard-Barton 1990), questions explored past decisions without mentioning OIPT. We started with experienced managers (+10 years), who were regularly involved in S&OP and who identified other relevant informants, and we continued interviews until reaching saturation (Yin 2017). We adapted the interview guide as new themes emerged. In total, 44 interviews with 28 informants were recorded and transcribed (see Table 2).

Archival documents (Table A1) helped to refine our interview questions and enhance the internal validity (Voss,

Table 2. Case study overview.

Case: Industry	Product family	Turnover (million €)/Employee, 2019	Engineer-to-order (ETO) decoupling setting		S&OP domain	Informant: job title (No. of interviews x length of interviews, in minutes)
			Engineering	Production		
A: Aerospace	Jet engine structures	670/2000	Design-to-order	Make-to-order	Independent local S&OP per plant Plan other standard product families	A1: S&OP coordinator (1 × 180) A2: S&OP coordinator (1 × 60) A3: Marketing director (2 × 60) A4: Logistics manager (2 × 60) A5: Logistics specialist (2 × 60) A6: Engineering manager (3 × 60) A7: Production manager (1 × 60) B1: S&OP coordinator (3 × 60) B2: S&OP coordinator (1 × 60) B3: Marketing director (1 × 30, 1 × 120) B4: Sales specialist (1 × 60) B5: Demand planner (3 × 30) B6: Engineering manager (2 × 120) B7: Production manager (1 × 90) B8: Procurement manager (1 × 60) C1: S&OP coordinator (4 × 30) C2: Marketing director (1 × 30) C3: Demand planner (1 × 90) C4: Sales specialist (1 × 90) C5: Plant manager (1 × 90) C6: Production manager (1 × 90) C7: Engineering manager (1 × 90) C8: Design estimators (1 × 60) D1: S&OP coordinator (1 × 60) D2: ETO planning manager (3 × 90) D3: Engineering manager (1 × 30) D4: Production manager (1 × 60) D5: Sales specialist (1 × 60)
B: Automotive	Customised electric vehicles	960/1000	Modify-to-order (minor <sup>a</sup> )	Finalize-to-order <sup>b</sup>	S&OP per 6 plants linked to a global group-level S&OP Plan other standard product families	
C: Medical systems	Sterilisers	3000/15600	Modify-to-order (major <sup>c</sup> )	Finalize-to-order	Independent local S&OPs per 1–3 plants Dedicated to ETO product families	
D: Industrial equipment	Industrial cranes	3330/16000	Modify-to-order (major)	Finalize-to-order	Independent local S&OPs per 1–3 plants Dedicated to ETO product families	

<sup>a</sup>Uses combinations of existing detailed designs as the starting point to fulfil each incoming order's specifications: integrations within the brief's parameters.

<sup>b</sup>When an order enters, the following process starts: assembly of standard items (available in stock) and purchasing and making the rest of the bill of material (BOM) items.

<sup>c</sup>Integrates existing standard designs as the starting point to fulfil each incoming order's specifications: forms, layouts, and integrations of designs available as stored/filed in expert systems or as drawings.

**Table 3.** Overall S&OP decision domains across case companies.

Decision domain	Company A	Company B	Company C	Company D
Demand forecast approval	Engineering and plant managers validate forecasts from account managers; formal verification meetings	Transportation providers contribute market intelligence; S&OP team applies segment-specific hit rates	Plant manager validates three probability-weighted scenarios; regional sales offices challenge assumptions	S&OP coordinator validates forecasts without cross-functional input
Engineering resource allocation	Engineering hours allocated per person/project; resource requests formalised through software system	Engineering hours categorised as core, consultant, or outsourced; allocation based on project complexity tier	Calculation department estimates total hours; application specialists validate technical requirements	Engineering resources considered after production capacity; allocations filtered through production representatives
Capacity constraint resolution	Three-level escalation protocol through engineering management; formal resolution procedures documented	Project complexity determines escalation path; chassis plant managers participate in constraint discussions	Supply chain issues escalated directly to executive team; plant manager aggregates department inputs	S&OP coordinator mediates between departments; no formal resolution protocol
Scenario selection	Executive team reviews multiple financially-integrated scenarios; risk tracking documentation required	S&OP team consolidates departmental inputs; delivery dates prioritised in final selection	Executive team selects from three weighted scenarios; plant manager provides validation	S&OP coordinator presents sales-focused scenarios; limited formal comparison methodology
Performance measurement	Standardised metrics track forecast accuracy, engineering utilisation, and hit rates; formal review cycles	Delivery adherence tracked against commitments; sales forecasting accuracy monitored	Actual costs compared against department estimates; limited formal metric documentation	Project timeline compliance tracked at basic level; no formal review process
Process participation	50+ participants across functions; engineering representatives at all decision levels	Up to 50 participants; participation determined by three-tier project complexity system	15 participants; plant manager central to all decision processes	10 participants; sales representatives dominate decision processes

Tsikriktsis, and Frohlich 2002). We ensured the accuracy of our case descriptions by sharing the final versions and interview transcripts with the corresponding informants. Thereafter, we conducted several workshops with the informants to validate our observations and discuss potential gaps. All documents were stored in a case database (Yin 2017).

### 3.4. Data coding

Our analysis phase (outlined in Figure 2) began once the case descriptions were finalised. In the first phase, we performed within-case analyses (Eisenhardt 1989), systematically reviewing each interview transcript to locate the uncertainty and equivocality instances identified through the data collection protocol. We then coded these instances inductively, grouping them by the type of information required for the underlying decision. This process involved systematic cross-case comparisons and validation with key informants (Gioia, Corley, and Hamilton 2013). Triangulation with multiple informants confirmed the relevance of each of the 19 identified distinct information categories, with supporting empirical evidence (exemplified in Annexes A–C).

In the second phase of the analysis, we used the descriptions and informant quotes to assess each category's uncertainty and equivocality levels on a five-point scale. We iteratively calibrated these assessments through cross-case comparison (Yin 2017). Following Gioia, Corley, and Hamilton (2013), we then aggregated the underlying drivers of uncertainty and equivocality into broader first-order categories (see Tables A2 and A3).

The third phase involved an OIPT-guided analysis. We identified case-specific IPRs for each information category, which were validated against the literature and through

cross-case comparisons before being aggregated into broader IPR categories. Using this IPR list, we assessed IPR–IPC configurations as either 'fit', 'partial fit', or 'lack of fit'. A fit indicated that strategies adequately addressed the IPR, a partial fit showed evidence of incomplete or inconsistent attempts, and a lack of fit signified a clear gap. We searched through the case descriptions for equivalent IPC-building strategies (see Annexes A–C) to ensure the validity of the lacking IPC when it was detected. Once the fit and lack-of-fit configurations were confirmed, the corresponding fulfilment forms and shortfalls in S&OP quality were identified across the four dimensions, per case and information category. The fit/lack-of-fit assessments underwent refinement iterations and are documented in Annexes A–C.

Finally, we conducted iterative cross-case comparisons to analyse patterns (Pratt 2008) of IPR–IPC fits and lack of fits. Cases with greater IPR fulfilment revealed specific IPC-building strategies (second-order constructs); we documented the links between IPRs, fit/lack-of-fit configurations, S&OP quality, and these strategies (Table A4). Further iterations aggregated these strategies into generic categories (first-order constructs), which formed the basis of our IPC-building framework for ETO S&OP (Table A5).

## 4. Findings

### 4.1. IPRs for ETO S&OP

The analysis of the information categories across the cases revealed ETO-specific IPRs driven by the two challenges of epistemic uncertainty (lack of knowledge) and equivocality (conflicting interpretations). These IPRs demand specific adaptations to traditional S&OP in order to accommodate

emerging information while maintaining system-wide stability. The following subsections divide these IPRs into three interconnected sorts reflecting project-level and system-wide challenges: demand-related, production-related, and supply chain.

#### 4.1.1. Demand-driven IPRs

Table 4 shows information categories that are transferable to most ETO environments with varying uncertainty and equivocality levels and their corresponding IPRs (Annexes A–C detail the coding). The four relevant categories outline demand-driven uncertainty and equivocality levels and the corresponding identified cross-case IPRs.

(1) Number of units per order: The epistemic uncertainty about final order size is evident in the limited visibility and predictability of order size (number of units) variability across the cases (D: 1–5 cranes, C: 1–20 sterilisers, A: 70–100 engine cases, B: 1–50 electric buses), thus requiring *order size forecasting, shared understanding of the assumptions, and order-size impact sensitivity analysis*. For instance, case A uses customer monitoring teams to continuously collect and analyse relevant data. For their part, in order to build shared understanding of the assumptions about what causes order size variability, cases B and C seek to intensify related cross-functional validation in S&OP by involving more relevant participants and by dedicating meeting protocols, respectively. Across all cases, order size variability entails necessary configurational adjustments in the capacity, production, and inventory dedicated to concurrent projects, which (according to informants from A and B) require estimations determined through, e.g. order-size impact sensitivity analysis.

(2) Sales process revenue: The limited predictability of the cases' sales process revenues reflects epistemic uncertainty about future tender outcomes. This is evident in the firms' low hit rates (A: 75% through specialised account management; B: 40% intercity, 80% coaches; C: regionally variable; and D: dealing with 90% customer specification uncertainty) and calls for *hit-rate forecasting and competitive and market intelligence integration*. For example, case A has dedicated integrated forecasting and feedback systems for hit rate predictions and continuously refines them through customer interactions, and case B uses a comprehensive tracking system that integrates tender status and delivery commitments among many other types related sales information. With regard to competitive and market intelligence integration (i.e. systematic collection, analysis, and dissemination of information about competitors, market trends, and the internal capabilities required to succeed in specific tenders), case C combines a 'sales force' knowledge repository (containing information on past bids, win/loss analysis, competitor profiles, and market reports) with regular regional validation meetings. These meetings serve as a forum for discussing competitor strengths and weaknesses, successful bidding strategies used in different regions, and the internal capabilities that are most critical for winning bids in each segment.

(3) Budget per order: Across all cases, the epistemic uncertainty in the budgeting process for individual projects stems

from a substantial information gap concerning the final project scope and costs. This limited visibility and predictability requires adaptive budget management that is able to *dynamically adjust budgets, validate cost assumptions, integrate resource availability, and proactively plan for potential deviations* throughout the project lifecycle. For instance, case A pushes for 10–20% contract flexibility in delivery commitments, to accommodate potential budget changes due to evolving specifications. Case C implements cost tracking and cost-change impact analysis to accommodate potential cost fluctuations arising from their extensive customer specifications, which exemplifies dynamic cost validation combined with a built-in early warning system. Case B employs differentiated configurator tools (complex vs. simplified) to match the budgeting approach to the project's complexity level, which improves the initial cost estimation accuracy and serves as simplified scenario planning. Case D faces the challenge of aligning budget estimates with material availability and assembly slots and thus needs integrated scenario planning for budget–resource alignment.

(4) Technical specifications: High equivocality across cases arises from translating often-vague or -evolving customer requirements into concrete, actionable technical specifications. This calls for *structured categorisation of specifications, real-time communication between sales and engineering teams for refinement, and systematic documentation of specification evolution*. For example, cases A, B, and C employ progressive specification development frameworks and categorise specifications into established groups in order to establish a degree of standardisation and reduce uncertainty. Case A's systematic approach to translating customer requirements into validated technical specifications exemplifies structured knowledge-sharing between sales and engineering and contributes to their documented specification evolution patterns. Case D faces broader specification ranges that cause higher initial uncertainty, requiring real-time communication channels between sales and engineering teams to facilitate progressive requirement refinement and to ensure operational flexibility.

#### 4.1.2. Production-driven IPRs

The subsequent categories in Table 4 outline production-driven uncertainty and equivocality levels and the corresponding IPRs.

(1) Overall product customisability: The varying degrees of product customisability identified across the cases—ranging from low (cases B and D, with over 70% component commonality) to moderate (case C, with ~50% commonality) to high (case A, with less than 50% commonality and no configurators)—introduce epistemic uncertainty. The lack of a priori knowledge about the feasible design space calls for a delineation of what can be customised (i.e. *customisation scope definition*) and to what extent (i.e. *design feasibility assessment*). For instance, due to low component commonality and a lack of configurators, case A defines customisation scope and assesses feasibility on a case-by-case basis; they rely heavily on direct co-creation with customers and university partners. In contrast, cases B and D achieve high component

Table 4. ETO-specific information categories and corresponding IPRs.

Information source	Information category*	Uncertainty/equivocality level**				Cross-case IPRs
		Case A	Case B	Case C	Case D	
Demand	Number of units per order	H / M	VH / H	M / M	L / L	Order size forecasting Shared understanding of assumptions causing order size variability Robust hit-rate forecasting
	Sales process revenue	H / L	VH / H	M / M	M / H	Competitive and market intelligence integration
	Budget per order	H / M	H / M	H / L	H / M	Integrated scenario planning for budget-resource alignment Early warning for budget deviations
	Technical specifications	M / L	M / L	M / L	H / M	Real-time communication between sales and engineering for refinement
Production	Overall product customisability	VH / H	L / L	M / M	L / L	Design feasibility assessment
	Customisable systems per product	L / L	VH / VH	M / M	L / L	Compatibility validation
	Production capacity flexibility	VH / H	L / L	M / M	M / M	Contingency planning
	Process quality	VH / H	H / H	H / H	L / L	Root cause analysis of quality issues
	Setup cost	M / M	H / H	VH / H	VH / VH	Setup cost data integration
	Production layout	VH / M	M / M	H / M	H / H	Layout change impact analysis
	Machine productivity	H / M	M / L	VH / H	VH / H	Root cause analysis for deviations from expected output
	Minimum inbound inventory	M / M	VH / H	H / H	H / M	Real-time tracking of customised inventory
	Labour skill development pace	VH / M	M / H	H / VH	L / VL	Skill-gap forecasting
	Labour type	L / L	H / M	VH / H	L / L	Predictive workload allocation
Supply chain	Internal labour availability	H / H	VH / VH	H / H	M / H	S&OP availability integration
	Labour productivity	VH / H	M / L	H / H	M / M	Integrated productivity forecasting
	Inter-resource equivalences	M / H	VH / VH	H / H	M / M	Cross-functional substitution coordination
	External labour or subcontractors	M / M	L / VL	M / H	H / H	External resource pool profiling
	Subcontracting cost	L / L	M / M	H / H	VH / VH	Strategic sourcing alignment

\*See Annexes A-C for examples of quotations and case-specific descriptions of uncertainty and equivocality corresponding to each information category.

\*\*VL: Very Low, L: Low, M: Moderate, H: High, VH: Very High.

commonality through structured modularity frameworks, which predefine a significant portion of the customisation scope and simplify feasibility assessment. Their knowledge integration platforms contain clearly defined rules and parameters for allowable customisations. Case C occupies an intermediate position. Their application specialists operate within defined boundaries, but with flexibility for major modifications. Accordingly, they must balance pre-defined customisation options with the ability to assess the feasibility of more extensive changes, which requires both structured information and expert judgement.

(2) Customisable systems per product: Across cases, the complexity of customisable systems within a product—ranging from relatively simple mechanical structures (cases A and D) to highly complex combinations of mechanical, electrical, electronic, fluid, and software systems (cases B and C)—generates equivocality. On several occasions, different technical domains interpreted system interactions differently, which impeded a shared understanding of how changes to one part could impact others. Establishing such an understanding requires *system interdependency mapping, configuration tracking and version control, and compatibility validation*. For example, case B manages the highest complexity, with up to 20 combined systems; it uses sophisticated multi-level configuration management systems that provide mechanisms for tracking configurations, mapping interdependencies, and validating compatibility across diverse technical domains, with their three-level project complexity assessment influencing these processes. Case C, with five combined systems, employs progressive validation processes for system compatibility and related validation. Their reliance on application specialists indicates a combination of formal and informal methods for mapping interdependencies and tracking configurations.

(3) Production capacity flexibility: Across the cases, epistemic uncertainty in production capacity flexibility stems from limited visibility and predictability. This lack of knowledge ranges from job shops with fixed machinery (case A) to unpredictable final testing (case C) and customised material-sensitive assembly (case D). Managing this uncertainty requires *current capacity assessment, capacity change impact prediction, and contingency planning*. For instance, case A relies on advanced simulation and modelling tools together with dedicated research initiatives to assess current capacity, to predict the impact of changes (like adding new equipment or changing the product mix), and to develop contingency plans for various production scenarios. Cases C and D exhibit moderate flexibility, with the ability to increase capacity by 20% and 30%, respectively, within 2–3 months, but they need robust methods for assessing the full implications. Case C's unpredictable final testing requires contingency planning to address potential delays and rework by integrating information from customer interactions into their capacity calculations. Case D needs accurate capacity change impact predictions to ensure that the customised material availability required for assembly and production plans align with resource constraints.

(4) Process quality: Epistemic uncertainty extends to the process quality for novel ETO configurations. The limited visibility and predictability of quality outcomes across certain cases—which are particularly challenged by stringent high-precision requirements (case A), component-intensive complex assembly (case B), and late customer involvement in product testing (case C)—call for *real-time process monitoring to track process deviations and root cause analysis of quality issues*. Informants at cases A, B, and C stressed the need for dynamic quality monitoring systems that enable participants in S&OP to track, predict, and timely analyse the root cause(s) of any deviations, as well as to document solutions and share lessons learned.

(5) Setup cost: The limited visibility and predictability of substantial setup costs represent a key area of epistemic uncertainty across the cases. Here, the uncertainty stems from highly variable operational factors, such as complex job shops (case A), batch production with setup-cost-sensitive design decisions (case B), and hybrid layouts with significant product size variations (1–100 m<sup>3</sup> sterilisers for case C, and 10–200 × 70 × 117 m<sup>3</sup> cranes for case D). These challenges make *setup cost modelling and setup data integration* necessary. The case companies respond to this epistemic challenge in different ways. For instance, Case A uses predictive cost modelling systems that are integrated into their S&OP. For their part, Case C's organisational structure creates equivocality. Their calculation department uses historical data and templates for setup cost modelling, but it remains disconnected from the forward-looking S&OP process. This functional silo prevents data integration and fosters conflicting interpretations of cost drivers. Case D exemplifies a third approach. They rely entirely on experienced specialists to estimate setup costs.

(6) Production layout: The epistemic uncertainty about future product specifications renders ETO production layouts highly unstable in all cases. This instability is evident in requirements for frequent machine reconfigurations in job shops (case A), partial line modifications (case B), and layout accommodations for significant product size variations (cases C and D). The resulting low predictability of layout dynamics requires IPRs that build physical adaptability into the production system, namely *rapid layout reconfiguration planning, real-time layout performance monitoring, and layout change impact analysis*. For example, case A faces the most dynamic environment featuring such needs, as they use highly configurable machines in a job shop that can be rearranged in the same week. This practice demands dynamic layout simulation systems that support rapid layout reconfiguration planning, as well as sophisticated tools for layout change impact analysis to predict the consequences of these frequent adjustments. In addition to these needs, cases B, C, and D deal with layout instability due to partial line modifications around fixed stations and extreme product size variations. Here, real-time layout performance monitoring is needed to quickly identify and address any disruptions caused by such changes.

(7) Machine productivity: A high degree of epistemic uncertainty in machine performance stems from a lack of

advance knowledge about future production runs. The unique material and size variations (cases C and D), tight precision requirements (case A), and novel production preparation variations for new components (case B) make performance difficult to predict. This knowledge gap calls for capabilities that enable *real-time machine performance tracking* and *root cause analysis for deviations from expected output*. The need for these adaptive capabilities is especially pronounced in cases C and D. On experiencing job duration deviations of up to 100% and 500%, respectively, the representatives of these companies confirmed their need for advanced material-machine interaction prediction systems to improve real-time machine performance tracking and sophisticated deviation root cause analysis capabilities in order to understand why such large deviations occur. Similarly, case A needs integrated maintenance and calibration tracking frameworks to manage the tight tolerances in aerospace manufacturing. Such frameworks help control known process variables (machine condition) to act as a buffer against the impact of unknown product variables (unique specifications), contributing to both real-time tracking and effective root cause analysis.

(8) Minimum inbound inventory: The epistemic uncertainty stemming from unknown demand signals for custom materials causes challenges in determining minimum required inbound inventory levels across multiple cases. This lack of knowledge—complicated by customisation at several product levels (case B), reliance on material requirement planning systems (case D), and multi-plant material requirements (case C)—calls for such capabilities as *demand signal processing for custom materials* and *real-time tracking of customised inventory*. For example, case B approaches demand signal processing through complex algorithms for determining safety stock levels, and material controllers are assigned to suppliers to monitor inventory status and flag potential shortages. However, the high stockout/obsolescence rate (35%) and the limited S&OP discussion on material issues indicate limitations in the adopted approaches. Cases C and D report similar stockout/obsolescence rates (20%). Case C's plant manager, also acting as the supply chain manager, reports supply chain issues during S&OP meetings; however, the lack of safety-stock-specific discussions indicates a potential gap in proactive demand signal processing. For its part, case D relies heavily on material requirement planning for material demand and inventory status monitoring, and some of their suppliers even have access to order specifications through this system.

(9) Labour skill development pace: One source of internal epistemic uncertainty lies in the pace of labour skill development, or how quickly and effectively specialist labour develops the necessary skills and productivity. This uncertainty was evident across cases in the long qualification times for aerospace engineers (case A), the unpredictable development of application specialists who need to become familiar with extensive, region-specific documentation (case C), and production engineers' struggles to grasp shop floor reconfigurability (case B). The required capabilities to reduce this epistemic uncertainty are *competency mapping*, *learning curve*

*prediction*, and *skill-gap forecasting*. For instance, case A uses internally developed software to manage engineering requests, but it primarily addresses resource allocation, which is not the core issue of predicting individual development trajectories. Case A needs better competency mapping to identify critical skills, as well as more accurate learning curve prediction methods and proactive skill-gap forecasting to anticipate future needs. Case C also needs these capabilities to address potential shortages of qualified specialists, which are currently not considered in their S&OP. Case B shows that even years of experience do not guarantee a full understanding of shop floor reconfigurability, which points to limitations in competency mapping (i.e. identifying the specific knowledge gaps) and long-term skill-gap forecasting.

(10) Labour type: High equivocality in defining the necessary labour types and skills required for project tasks is evident at cases B and C, which face frequent deviations of actual from planned engineer task completion times (50%). This ambiguity stems from a reliance on the implicit knowledge of individual managers, rather than a systematic up-to-date record of employee capabilities and workloads. Accordingly, resolving such conflicting interpretations requires *dynamic skill profiling* to maintain a current and detailed record of employee skills, *skill-based task analysis* to define the skills needed for each task, and *predictive workload allocation* to dynamically allocate labour based on skills and availability. Informants at case C confirm the reliance on implicit knowledge and a lack of formal methods or S&OP integration. At case B, team managers validate resource needs, but their assessments lack a granular, dynamic skill profiling that goes beyond broad job titles to capture specific expertise within each category. In addition, case B lacks integration with S&OP concerning predictive workload allocation at a strategic level and, consequently, fails to proactively address potential skill shortages. Informants at cases A and D attribute their lower deviations (25% and 20%, respectively) to structured approaches to dynamic workload balancing that reduce such interpretative ambiguity.

(11) Internal labour availability: High equivocality often obscures the true availability of internal labour availability, particularly for specialised engineering resources. This problem arises from such factors as complex organisational structures and reliance on fragmented informal systems (cases B, C), as well as a disconnect between detailed planning and higher-level S&OP processes (cases A, B, C, D), all of which can create multiple, often conflicting versions of resource capacity. For instance, case B's complex organisational structure, where engineers contribute across multiple functions, is paired with restricted access to availability information and a lack of detailed engineering capacity planning in S&OP, which limits the visibility of internal labour availability. Case C relies on sophisticated macros-intensive spreadsheets for local-level planning that are not integrated into the S&OP process, which obstructs visibility at the strategic level. These limitations demonstrate a need for *centralised availability tracking* to consolidate information, *role-specific availability views* tailored to different stakeholders (e.g. project managers vs. S&OP planners), and *S&OP availability integration* to

incorporate engineering capacity into strategic decision-making.

(12) Labour productivity: Across cases, high equivocality in assessing labour productivity, especially for specialised engineering roles, stems from scattered knowledge of engineer capabilities (case A), reliance on implicit understanding (case C), and inconsistent use of skill matrices (case D). Thus, building a shared objective basis for productivity assessment requires *unified productivity tracking* (a centralised system for capturing planned vs. actual hours), *skill-based performance analysis* (connecting productivity to specific skill sets), and *integrated productivity forecasting* (using historical data to predict future performance). For instance, case B uses established skill matrices wherein engineering managers maintain comprehensive knowledge of departmental capabilities. Cases A and D use internally developed software and spreadsheets for similar purposes, but the knowledge of their engineer capabilities is dispersed among a number of engineering managers, and their skill matrices are not universally applied or consistently updated. Case C relies solely on individual managers' implicit knowledge (through experience and personal relationships) to understand engineer capabilities. The lack of a systematic shared basis for analysis at cases A, C, and D perpetuates equivocality and limits visibility around actual productivity. The difficulty in predicting learning curves (from previous analyses) is a consequence of this inability to establish a shared objective performance baseline.

(13) Inter-resource equivalences: Across the cases, high equivocality characterises the potential for employees to substitute for one another (inter-resource equivalence), which is a problem rooted in uncoded, often-conflicting tacit knowledge. This is evident in reliance on personal experience (cases A, C), a mix of rules and experience (case B), and incomplete knowledge of existing rules (case D). Such disparate and subjective views on inter-resource equivalence indicate a need for *substitution rule documentation* (making the rules comprehensive and accessible to all relevant personnel), *skill-based substitution mapping* (linking substitutability to specific skill sets, not just individuals), and *cross-functional substitution coordination* (channels for substitution requests and approvals). For instance, case C relies entirely on personal experience for substitution decisions, without a shared basis for validation. Case B uses a mix of established rules and experience, but the inconsistency in awareness concerning substitute possibilities indicates that different managers are operating with different interpretive schemas. These cases demonstrate the need to translate informal experiential knowledge into a formal system, which would involve two distinct actions: first, to document the substitution rules, making them explicit and accessible across the organisation; second, to systematically map which employee competencies are transferable across different roles. Together, these actions create a substitution framework based on objective capabilities rather than a manager's personal judgement or memory. For its part, Case B does employ interdepartmental liaison roles, but their inconsistency indicates a need for formalised cross-functional substitution coordination.

#### 4.1.3. Supply chain-driven IPRs

The last two categories in Table 4 outline supply-chain-driven uncertainty and equivocality levels and the corresponding IPRs.

(1) External labour/subcontractors: Across several cases, the epistemic uncertainty surrounding external labour markets stems from the limited visibility of subcontractors' availability and expertise, and from the unpredictable nature of recruitment timelines. This knowledge gap calls for building IPC in the form of *integrated make-or-buy analysis*, *proactive sourcing and vetting*, and *external resource pool profiling*. For example, case A's dedicated make-or-buy analysis in early S&OP steps is an effective strategy for reducing this type of uncertainty; their systematic comparison of internal versus external resources, supported by an external skills-tracking program, builds a supportive knowledge base. In contrast, case D's reactive approach and case C's ad-hoc methods demonstrate a failure to build this capacity. Their inability to evaluate external resources before they are urgently needed, or to maintain up-to-date information on subcontractor capabilities, leads to suboptimal decisions rooted in unresolved epistemic uncertainty.

(2) Subcontracting cost: Another form of epistemic uncertainty in some cases arises from the limited predictability of subcontracting costs when dealing with dynamic markets (cases C, D) or when dedicated strategies are lacking (case B). This knowledge gap requires *subcontracting cost driver analysis*, *dynamic cost forecasting*, and *strategic sourcing alignment*. For instance, case D outsources over half of its work without specific cost management strategies; the same applies to case C, which relies on informal methods (e.g. reviewing spreadsheets, consulting HR) for cost estimates. This reactive approach ignores subcontracting cost implications as seen through, e.g. cost driver analysis (understanding why costs vary). Moreover, both cases lack dynamic cost forecasting (predicting cost changes based on market trends) and strategic sourcing alignment (integrating subcontracting cost considerations into overall business planning and S&OP). Case B provides an example of strategic sourcing alignment. They collect extensive data through local HR and maintain long-term partnerships with staffing companies to control the associated quality and prices. Their three-level allocation system and clear delineation of core competencies illustrate that cost-effectiveness evaluation frameworks must be established to support strategic sourcing.

#### 4.1.4. Aggregate IPRs for ETO S&OP

We synthesised the identified IPRs (Table 4), which serve as second-order constructs, into 8 broader first-order categories, shown in Table 5 (column 1). 4.2 Fulfilment forms and shortfalls in S&OP quality and corresponding IPC-building strategies

Table 5 summarises other findings in addition to the aggregate IPRs. Each identified (second-order, column 2) IPR calls for visibility, predictability, or both (column 3) and operates at the project level (i.e. individual ETO orders), system level (i.e. organisation-wide processes), or both (column 4). The table also summarises the identified IPR-IPC fit/lack-of-fit

Table 5. Identified IPRs, required capability, operational level, IPR-IPC fits/misfits, S&OP quality, and IPC-building strategies across cases.

First-order IPR	Second-order IPR	Required capability	Level	Overview of cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies
1. Demand understanding requirements:	Order size forecasting	Predictability	Project	A: Fit (Continuous customer data analysis), B, C, D: Misfit (No explicit forecasting) All: Misfit (No explicit implementation)	IQ	1. Dedicated customer monitoring systems
	Order-size impact sensitivity analysis	Predictability	Project		PQ, AQ	2. Configurational impact simulation systems
	Shared understanding of order size variability assumptions	Predictability and visibility	System	A, B, C: Fit (Cross-functional S&OP)	AQ, CE	3. Cross-functional validation frameworks
	Robust hit-rate forecasting	Predictability	Project	A: Fit (Integrated forecasting & feedback), B: Partial fit (Tracking but no refinement), C: (Regionally variable), D: Misfit (High specification uncertainty). C: Fit (Knowledge repository & meetings)	IQ, PQ	4. Integrated hit-rate forecasting and feedback systems
2. Budget management requirements	Competitive and market intelligence integration	Predictability and visibility	System		IQ, CE	5. Centralised market knowledge repositories with formalised validation forums
	Dynamic adjustments of budgets	Predictability and visibility	Project	A: Partial fit (10-20% flexibility, mechanisms unclear), B, C, D: Misfit	PQ, AQ	6. a. Contractual and budget flexibility frameworks b. Budget flexibility frameworks
	Dynamic validation of cost assumptions	Predictability and visibility	System	C: Fit (Cost tracking & impact analysis)	IQ, PQ	7. Cost driver tracking and review
	Integrated scenario planning for budget-resource alignment	Predictability	System	B: Partial fit (Configurator tools), D: Misfit (Recognises need, lacks integration), A, C: Misfit C: Partial fit (Early warning system present), A, B, D: Misfit	PQ, CE	8. a. Resource-constrained scenario planningb. Multi-dimensional resource-budget simulation tools
3. Specification management requirements	Early warning for budget deviations	Visibility	Project		IQ, PQ	9. Real-time budget monitoring and alerting Proactive budget deviation detection systems
	Structured categorisation of specifications	Visibility	Project	A, B, C: Fit (Progressive frameworks), D: Misfit	PQ, IQ	10. Specification taxonomy and classification
	Systematic documentation of specification evolution	Visibility	Project	A: Fit (Documented evolution, formality unclear)	IQ	11. Implement a centralised, version-controlled specification management system
	Real-time communication between sales and engineering	Visibility	Project	D: Misfit (Needs real-time channels)	AQ, CE	12. Cross-functional specification refinement platforms
4. Production configuration requirements	Customisation scope definition	Visibility	Project	B, D: Fit (Structured modularity), C: Partial fit (Defined boundaries, some flexibility), A: Misfit ("Case-by-case" approach)	PQ, AQ	13. Modular boundaries system with knowledge integration platforms
	Design feasibility assessment	Predictability	Project	B, D: Fit (Simplified assessment), C: Partial fit (Structured & expert judgement), A: Misfit ("Case-by-case" assessment)	PQ, CE	14. Multi-level feasibility assessment framework
	System interdependency mapping	Visibility	Project	B: Fit (Multi-level configuration management), C: Partial fit (Simpler approaches), A, D: Misfit	PQ, IQ	15. Multi-level dependency modelling and visualisation
	Configuration tracking and version control	Visibility	Project	B: Fit (Multi-level configuration & informal methods), A, D: Misfit B: Fit (Compatibility validation), C: Partial fit (Progressive validation, manual), A, D: Misfit	PQ, IQ	16. Complexity-adaptive configuration management system
	Compatibility validation	Predictability	Project		PQ, CE	17. Progressive and automated compatibility validation

(continued)

Table 5. Continued.

First-order IPR	Second-order IPR	Required capability	Level	Overview of cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies
	Rapid layout reconfiguration planning	Predictability	Project	A: Partial fit (Recognized need, lacks full implementation), B, C, D: Misfit (No explicit planning)	PQ, CE	18. Dynamic production layout simulation and optimisation
	Real-time layout performance monitoring	Visibility	Project	B, C, D: Partial fit (Recognise need, lack full implementation), A: Misfit	IQ, AQ	19. Real-time layout performance monitoring and disruption detection system
	Layout change impact analysis	Predictability	Project	A: Fit (Impact analysis tools)	PQ	20. Integrated layout change impact assessment tools
5. Production monitoring requirements	Current capacity assessment	Visibility	Project	A: Fit (Advanced simulation & modelling), C, D: Partial Misfit (Recognise need, lack robust methods), B: Misfit	IQ, PQ	21. Multi-parameter capacity modelling and analysis system
	Capacity change impact prediction	Predictability	Project	A: Fit (Predictive tools), D: Partial fit (Recognises need), B, C: Misfit	PQ, AQ	22. Predictive capacity planning with scenario modelling
	Real-time process deviation monitoring	Visibility	Project	A, B, C: Partial fit (Recognise need, lack full implementation), D: Misfit	IQ	23. Real-time SPC and deviation alerting system
	Real-time machine performance tracking	Visibility	Project	C, D: Partial fit (Recognise need), A: Fit (Integrated tracking), B: Misfit	IQ, PQ	24. Machine-level data acquisition and predictive analytics for material-machine interaction
	Root cause analysis of quality issues	Predictability and visibility	System and project	A, B, C: Partial fit (Recognise need, lack full implementation), D: Misfit	PQ, IQ, CE	25. Structured root cause analysis with knowledge sharing
	Root cause analysis for performance deviations	Predictability and visibility	System and project	C, D: Partial fit (Recognise need), A: Fit (Links machine condition to output), B: Misfit	PQ, IQ, CE	26. Integrated root cause analysis for performance with condition-performance correlation
	Contingency planning	Predictability	System	A: Fit (Advanced simulation & contingency plans), C: Partial fit (Recognises need), B, D: Misfit	PQ, AQ	27. Scenario-based contingency planning with simulation-based evaluation
6. Resource planning requirements	Setup cost modelling	Predictability	Project	A: Fit (Predictive cost modelling), C: Partial Misfit (Historical data, not in S&OP), D: Potential Misfit (Reliance on experience), B: Misfit	PQ, IQ	28. Activity-based predictive setup cost modelling
	Setup cost data integration	Visibility	System and project	All: Misfit (Separation of cost modelling and S&OP)	IQ, AQ	29. Cross-functional setup cost integration with S&OP
	Demand signal processing for custom materials	Predictability	System	All: Misfit (Need improved competency mapping)	IQ, PQ	30. Competency taxonomy and skills inventory system
	Real-time tracking of customised inventory	Visibility	System	All: Misfit (Unpredictable skill development)	PQ, IQ	31. Skill development trajectory modelling
7. Labour capacity management requirements	Competency mapping	Visibility	System	All: Misfit (Lack proactive skill-gap forecasting)	PQ, AQ	32. Proactive skill gap analysis and forecasting
	Learning curve prediction	Predictability	System	All: Misfit (Limited dynamic skill profiling)	IQ, AQ	33. Real-time skill and capability tracking system
	Skill-gap forecasting	Predictability	System	C: Misfit (Lack of formal methods), B: Partial fit (Team manager validation, lacks granularity), A, D: Misfit	PQ, CE	34. Task-skill decomposition and requirement specification
	Dynamic skill profiling	Visibility	System	A, D: Fit (Structured workload balancing), B, C: Misfit (Lack of integration/proactive addressing)	PQ, AQ	35. Skills-based resource allocation and workload balancing system
	Skill-based task analysis	Predictability and visibility	System	All: Misfit (Fragmented availability information)	IQ	36. Enterprise-wide unified availability management system
	Predictive workload allocation	Predictability	System and project	All: Misfit (Limited customised views)	AQ, IQ	37. Role-customised availability dashboards and interfaces
	Centralised availability tracking	Visibility	System	All: Misfit (Disconnect between planning and S&OP)	AQ, CE	38. Workforce availability integration with S&OP

(continued)

Table 5. Continued.

First-order IPR	Second-order IPR	Required capability	Level	Overview of cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies
	Role-specific availability views	Visibility	System	B: Partial fit (Established skill matrices), A, C, D: Misfit (Lack of systematic data collection)	IQ, PQ	39. Centralised time tracking for productivity measurement
	S&OP availability integration	Visibility	System	All: Misfit (Limited connection between skills and performance)	PQ	40. Competency-based performance analysis
	Unified productivity tracking	Visibility	System	All: Misfit (Difficulty predicting learning curves)	PQ	41. Productivity forecasting with historical data and skill integration
	Skill-based performance analysis	Predictability and visibility	System	All: Misfit (Limited formalisation of substitution rules)	IQ, AQ	42. Formalised substitution rule repository and governance system
	Integrated productivity forecasting	Predictability	System	All: Misfit (Same as Strategy 42)	PQ	43. Competency-based substitution matrix and equivalence framework
	Substitution rule documentation	Visibility	System	B: Partial fit (Liaison roles, inconsistent), C: Misfit (Reliance on experience), A, D: Misfit	AQ, CE	44. Formalised interdepartmental substitution process and platform
	Skill-based substitution mapping	Visibility	System	B: Partial fit (Complex algorithms, high stockout/obsolescence), C, D: Misfit (High stockout/obsolescence, lack of discussion), A: Misfit	PQ, IQ	45. Adaptive forecasting for custom material demand
	Cross-functional substitution coordination	Visibility	System	B, D: Partial fit (Some monitoring/supplier access), C: Misfit (Reactive reporting), A: Misfit	IQ, AQ	46. Real-time custom material tracking
8. External resource management requirements	Integrated make-or-buy analysis	Predictability and visibility	System	A: Fit (Make-or-buy analysis in S&OP), C, D: Misfit (Lack of formal analysis in S&OP)	PQ, AQ, CE	47. Cross-functional make-or-buy decision framework for S&OP
	Proactive sourcing and vetting	Predictability	System	A: Partial fit (Tracks external skills), C, D: Misfit (Fail to identify/evaluate proactively)	PQ, IQ	48. Proactive supplier qualification and relationship management
	External resource pool profiling	Visibility	System	A: Partial fit (Tracks external skills, lacks comprehensive profiling), C, D: Severe Misfit (No up-to-date information, ad-hoc knowledge)	IQ	49. Subcontractor database and capability matrix
	Subcontracting cost driver analysis	Predictability and visibility	System	D: Misfit (No specific cost management), C: Misfit (Informal methods), B: Partial fit (Extensive data collection, partnerships), A: Misfit.	PQ	50. Subcontracting cost driver analysis and variability modelling
	Dynamic cost forecasting	Predictability	System	C, D: Misfit (No cost change prediction), B: Partial fit (Partnerships for stability, limited forecasting), A: Misfit	PQ	51. Market-sensitive subcontracting cost forecasting
	Strategic sourcing alignment	Predictability and visibility	System	B: Partial fit (Allocation system, competency delineation), C, D: Misfit (No strategic sourcing alignment), A: Misfit.	AQ	52. Strategic sourcing integration with S&OP for competency development

Notes. <sup>1</sup> First-order IPR categories represent logically clustered information processing requirements (IPRs) in ETO environments.

<sup>2</sup> Second-order IPRs represent specific IPRs identified through cross-case analysis.

<sup>3</sup> Level indicates whether the requirement primarily applies to ETO projects and/or the underlying system.

<sup>4</sup> S&OP quality gap: IQ (Informational Quality), PQ (Procedural Quality), AQ (Alignment Quality), CE (Constructive Engagement).

<sup>5</sup> See Table A4 for more details about the cross-case IPR-IPC fit/misfit, corresponding S&OP quality gap, and potential IPC-building strategies.

<sup>6</sup> See Annexes A–C for examples of quotations and case-specific descriptions of IPR, IPC, and corresponding fits and misfits within planning quality dimensions.

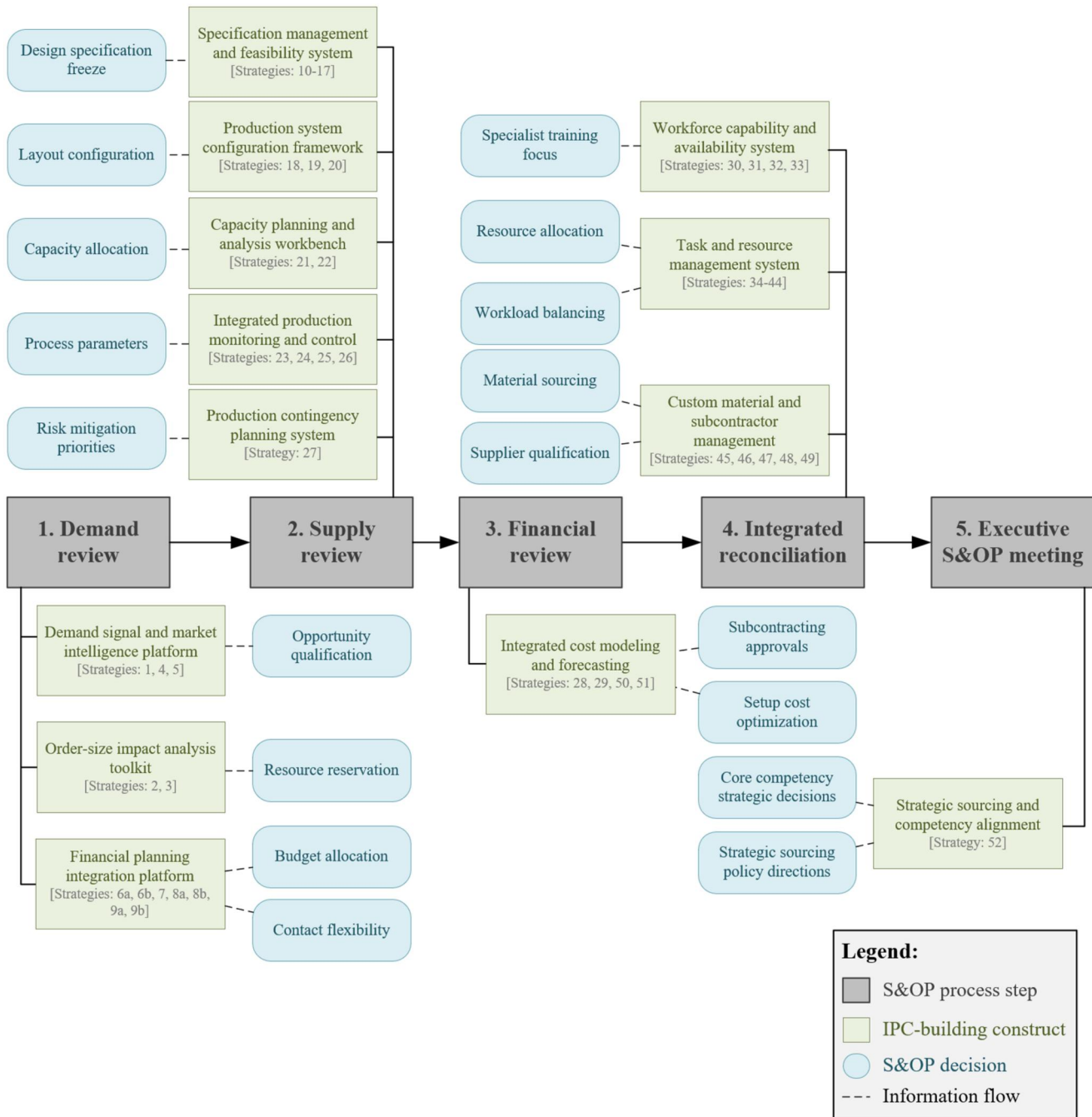


Figure 3. IPC-building framework for ETO S&OP.

configurations across the four cases (column 5); these were derived from the detailed case analyses (Annexes A–C) and matched with the corresponding S&OP quality dimensions (column 6). The fulfilment forms and shortfalls in the aligned S&OP quality dimension, in turn, informed the corresponding IPC-building strategies (column 7). These strategies represent a comprehensive set of concrete approaches for developing the IPC needed in S&OP in ETO environments. For instance, case A demonstrates adequate IPC for ‘order size forecasting’ through ‘dedicated customer monitoring systems’; at the same time, all case companies exhibit an IPR–IPC lack of fit regarding ‘order-size impact sensitivity analysis’, which indicates a widespread need for ‘configurational impact simulation systems’. Table A4 provides a more detailed breakdown

of Table 5, including specific examples of fit/lack-of-fit configurations, the rationale for aligned S&OP quality dimensions, and further elaboration on the IPC-building strategies.

#### 4.2. IPC-building framework for ETO S&OP

The 52 (second-order) IPC-building strategies identified from the case analysis were synthesised into 13 (first-order) categories, as shown in Table A4. These strategies were then aligned with relevant S&OP activities based on the key functional decisions they support, thereby forming our proposed IPC-building framework for ETO S&OP, visualised in Figure 3. The figure illustrates how the emerging strategies connect S&OP process steps with key decisions through structured

information flows. The underlying architecture offers a practical roadmap for implementing effective strategies to enhance S&OP performance in ETO environments.

## 5. Discussion

### 5.1. Theoretical implications

#### 5.1.1. Reflections from ETO S&OP contexts on OIPT (uncertainty, equivocality, and IPRs)

Our findings offer opportunities to advance the OIPT perspective in three primary areas: (1) equivocality, (2) interactions between uncertainty and equivocality, and (3) emerging IPRs.

(1) Equivocality: Traditional OIPT applications prioritise uncertainty reduction (Foerstl, Meinschmidt, and Busse 2018; Schlegel, Birkel Hendrik, and Hartmann 2021). ETO S&OP is subject to substantial equivocality, shaped by embedded ambiguity and the resulting cross-function conflicts in understanding. For example, case B's customisable systems per product (Table 4) demonstrated high equivocality despite their technological sophistication: engineers, production managers, and sales—each with their distinct epistemological lens—interpret specifications differently. This conflict stems from 'incompatible interpretive schemas', not simply poor communication (Brusoni and Prencipe 2006); much of the critical knowledge in ETO is tacit or 'sticky' and thus hard to formalise (Sjödín, Frishammar, and Eriksson 2016).

Furthermore, equivocality in ETO S&OP possesses a temporal element, wherein initial interpretive differences can magnify over time (Sloot, Voordijk, and Volker 2025), as evident in the cross-case 'system interdependency mapping' lack-of-fit configurations. Addressing this requires iterative clarification and cross-functional engagement—namely sensemaking, sensegiving, sensedemanding, and joint sensemaking to negotiate shared meaning (Majchrzak et al. 2000), beyond mechanistic information-sharing (Srinivasan and Swink 2018), as well as a proper choice of communication medium (Rice 1992).

(2) Interactions between uncertainty and equivocality: The interactions in Tables 4 and 5 imply a dynamic interplay between uncertainty and equivocality that goes beyond simplistic models (e.g. Bensaou and Venkatraman 1995; Daft and Lengel 1986; Weick 1979). Reducing equivocality in technical specifications (Table 4) through structured categorisation (i.e. specification taxonomy and classification) must happen before uncertainty can be addressed. Conversely, the customisable systems per product in case B show a multiplicative effect, where high uncertainty and equivocality require substantially more IPC jointly than separately. The gradual unfolding of requirements in ETO also creates shifting dynamics. Early equivocality reduction can increase later uncertainty by uncovering previously unknown gaps, a nuance that is absent from foundational models (e.g. Galbraith 1977).

These interactions are also domain-specific, in that uncertainty often dominates production categories (like machine productivity), while demand categories are characterised by greater equivocality. The connection can also be recursive.

Resolving uncertainty can create new equivocality in technical specifications, which contests unidirectional views (e.g. Daft and Lengel 1986). Certain known factors need refinement in ETO contexts. For instance, according to Rice (1992), task clarity should lessen the uncertainty–equivocality link, yet internal labour availability in our analysis shows high equivocality across cases, no matter the uncertainty, which suggests that ETO's specialised knowledge overrides task structure. In addition, product architecture appears to be more influential than technological maturity, with complex organisational structures amplifying both uncertainty and equivocality.

To capture these non-linear interactions going beyond simplistic effects, we propose four theoretical extensions for future research: cumulative equivocality and cascading uncertainty (how the two manifest through temporal dynamics), cross-domain amplification (how uncertainty in one area fuels equivocality in another), interpretive path dependency (how early equivocality resolution influences later uncertainty), and expertise asymmetry (how high expertise increases equivocality).

(3) Emerging IPRs: Our findings show ETO-specific IPRs for S&OP that arise from the interaction of extreme customisation, project-based work, and complex interdependencies. IPRs for demand understanding and production configuration are central to any responsive supply chain (Krajewski, Wei, and Tang 2005), where they typically support the management of volume and mix fluctuations within stable product families. ETO S&OP shifts the focus from managing variance within predefined boundaries to managing the ongoing negotiation and emergence of the boundaries themselves.

Other IPRs reveal the limits of existing planning frameworks. Specification management IPRs overlap conceptually with concurrent engineering (Terwiesch and Loch 1999), but the latter typically entails analysing dependencies at a fixed point in time; consequently, concurrent engineering underemphasises the continuous iterative unfolding of specification evolution in ETO, where design decisions ripple through the entire system. Similarly, budget management IPRs reveal a scenario planning gap that finds parallels in project management's 'unknown unknowns' (Pich, Loch, and Meyer 2002), but those models often neglect ETO's operational complexities, with internal interdependent decisions constantly reshaping project scope and resource needs.

The common thread is that these existing models are not built for the epistemic uncertainty of ETO, where a lack of knowledge about final specifications is the core problem (Benjaminsen and Sørnes 2026). Complexities such as concurrent engineering become challenging when the planning process lacks the flexibility for iterative adaptation. Therefore, the unique IPRs emerging from this environment do not call for the refining of static models; instead, in reference to recent adaptable supply chain planning frameworks (e.g. Sengupta et al. 2025), we see a demand for fundamentally different planning frameworks.

### 5.1.2. Reflections on ETO S&OP literature

Our findings offer opportunities to advance the S&OP literature in four primary venues: (1) ETO S&OP, (2) S&OP maturity models, (3) S&OP quality, and (4) IPR–IPC fit/lack-of-fit analysis.

(1) ETO S&OP: Our findings confirm that standardised S&OP cannot be applied to ETO environments, in line with other works (Bhalla et al. 2023b; Kristensen and Jonsson 2018; Shurrab, Jonsson, and Johansson 2022b). The core assumptions (stable product definitions, predictable demand, short lead times) break down in the ETO context amid the evolving requirements and project-specific complexities. Traditional S&OP models assume clearly-bounded functional structures (Tuomikangas and Kaipia 2014) that do not align with ETO's need for complex cross-functional integration, thus hindering structural synchronisation (Zorzini et al. 2008) and timely information exchange. The standardisation-oriented culture of traditional S&OP (Goh and Eldridge 2024) also clashes with the adaptive thinking we found to be essential for ETO flexibility.

Existing ETO frameworks for tactical planning are often too narrow. They focus on aspects like delivery dates (Bhalla, Alfnes, and Hvolby 2023a) or sequential decisions (Shurrab, Jonsson, and Johansson 2022b), but they often lack a holistic information-centric approach. Technology-driven solutions, such as big data analytics (Schlegel, Birkel Hendrik, and Hartmann 2021), address uncertainty but leave the pervasive equivocality in ETO environments largely untouched. Our IPC-building framework (Figure 3) addresses the double challenges with 52 actionable strategies designed to build specific adaptive capabilities. Some strategies build technical capability to manage epistemic uncertainty; for instance, configurational impact simulation systems (Strategy 2) build PQ for managers to model the unknown impacts of order size changes. Other strategies build social capability to resolve equivocality. For example, cross-functional validation frameworks (Strategy 3) foster AQ and a structured process for reconciling conflicting assumptions. Linking these mechanisms with the relevant S&OP stages offers a holistic view tailored to the ETO context.

(2) S&OP maturity models: Our findings offer a complement to traditional S&OP maturity models (Danese, Molinaro, and Romano 2018; Grimson and Pyke 2007), which are not well-suited for ETO settings. Traditional models suffer from the theoretical flaw of assuming linear progression, show empirical inconsistencies when 'mature' firms underperform, lack specificity, and underemphasise qualitative factors like uncertainty (Hulthén, Näslund, and Norrman 2016). Our S&OP quality framework, based on OIPT and the work in Oliva and Watson (2011), offers an alternative view centred on information processing quality that tackles uncertainty and equivocality, is context-sensitive, focuses on capabilities, and acknowledges adaptation, thereby providing a granular view of the capabilities ETOs require.

(3) S&OP quality: Our findings advance the framework from Oliva and Watson (2011) by operationalising its dimensions in the ETO context. Here, the framework's value lies in its ability to assess the capabilities needed for ETO's

intertwined challenges. PQ and IQ together build the technical capacity to manage epistemic uncertainty through adaptive processes and systematic knowledge-gathering, while AQ and CE build the social capacity to resolve equivocality by facilitating the sensemaking and negotiation required to forge shared understanding from conflicting interpretations. These dimensions seem interdependent; the interplay between technical and social capabilities is evident in our specification management findings, where structured categorisation (a function of PQ) and cross-functional conversations (a function of AQ) are mutually supportive. The strength of this integration varies with contextual factors, such as knowledge domain asymmetry (Carlile 2004), temporal fragmentation (Gosling, Hewlett, and Naim 2017), and recursive specification development (Zorzini et al. 2008).

(4) IPR–IPC fit/lack-of-fit analysis: The ETO literature explains the cross-case failure to grasp the full consequences of changes in order size across interconnected projects (order-size impact sensitivity analysis in Table 5). Hans et al. (2007) attributed this failure to structural barriers, including resource fungibility (resources not easily swapped), temporal interdependence between projects (one project's size change impacting others with respect to resources), and scope elasticity (size changes often triggering requirement shifts beyond simple scaling). This non-linearity explains why simple proportional scaling assumptions fail and why accurate forecasting does not translate to accurate impact assessment. Common analytical tools like the critical path method (CPM) and the program evaluation and review technique (PERT) compound the problem. They often miss these resource interactions, which creates an artificial sense of independence between projects (Carvalho, Oliveira, and Scavarda 2015).

### 5.2. Practical implications

The findings offer practical implications for ETO manufacturers in terms of guided capability-building, organisational culture, and digital transformation.

First, our IPC-building framework (Figure 3) offers a structured methodology for developing adaptive capabilities. When used with the findings in Table 5, it functions as a diagnostic tool. Managers can identify specific lack-of-fit configurations where their firm lacks either the technical capacity to reduce epistemic uncertainty or the social capacity to resolve equivocality; they can then prioritise the IPC-building strategies to target these specific gaps. For instance, for skills-based resource allocation (Strategy 35), a firm might first create a skills and competency matrix (Strategy 30), then deploy software for real-time skills tracking (Strategy 33), predictive workload distribution (Strategy 35), and role-based views of availability (Strategy 37). Integrating the outcomes of these strategies with S&OP (Strategy 38) ensures that resource constraints inform tactical and strategic decision-making.

Second, a culture of learning and adaptation is a prerequisite for navigating effective adoption of the framework. Many of the identified strategies use learning as the primary mechanism for reducing epistemic uncertainty, as well as regular structured cross-functional interactions (seen in cases A, B,

and C) to resolve equivocality through alignment. However, these interactions are only effective when they encourage open communication and collaborative sensemaking, which is usually enabled by psychological safety (Edmondson 2018). These practices build resilience, but they require structural support to prevent unintended negative consequences.

Third, digital technologies are central to managing epistemic uncertainty. Digital twins can facilitate real-time layout performance monitoring (Strategy 19) through high-fidelity virtual representations (Tao et al. 2019), while AI-driven analytics can improve capacity change impact prediction (Strategy 22) through heterogeneous data fusion (Wuest et al. 2016). Nevertheless, these technologies are less effective at resolving equivocality, as conflicting interpretations require human judgement and collaborative sensemaking. Digital tools can serve as boundary objects to support this human-centric process, but they cannot replace it. Moreover, an AI's system 'black box' nature (Cheng et al. 2022) can hinder the transparency needed for shared understanding. Thus, a socio-technical approach is needed wherein technology augments human expertise rather than replacing it.

## 6. Conclusion

Standard S&OP approaches fall short in the dynamic environment of ETO. We empirically examined this mismatch and found that the unique IPRs of ETO demand shifting S&OP from a static planning tool to an adaptive process that manages both epistemic uncertainty and equivocality.

A core contribution of this research is the IPC-building framework for ETO S&OP, which encompasses 52 actionable strategies for building this adaptive capability. The framework provides the means to foster both organisational learning to reduce epistemic uncertainty and collaborative sensemaking to resolve equivocality. We also show how the S&OP quality dimensions can be repurposed as an analytical tool, whereby PQ and IQ assess a firm's capacity for learning and AQ and CE assess its capacity for sensemaking.

This study is not without limitations. The focus on large-sized manufacturers may limit the transferability of the findings to small and medium-sized ETO enterprises. Furthermore, retrospective accounts from the informants create the potential for recall bias. The cross-sectional data collection also restricts the ability to observe IPR-IPC dynamics over time. Finally, the case study approach limits generalisability and the establishment of definitive cause-and-effect relationships.

These limitations offer several avenues for future research. For one, longitudinal studies are encouraged in order to understand how organisations develop IPC over time and thus to capture the processes of organisational learning and adaptation. Such studies would ideally combine planned structure with flexibility to capture emerging phenomena (Eisenhardt and Graebner 2007), use techniques like temporal bracketing (Langley et al. 2013), and employ theoretical sampling for broader representation (Corbin and Strauss 2015). In addition, comparative studies across diverse ETO subsectors could reveal context-specific IPR variations; here, action research could validate the effectiveness of specific IPC-

building strategies. Finally, further investigation into the interplay between digital technologies and IPR-IPC fit, including the specific individual competencies and culture, would also be a valuable complement.

As ETO environments grow more complex, competitive advantage will depend on an organisation's ability to master information processing. This research is a step towards building the corresponding adaptive S&OP capabilities.

## Author contributions

CRediT: **Hafez Shurrab**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing – original draft, Writing – review & editing; **Patrik Jonsson**: Conceptualization, Methodology, Resources, Supervision, Writing – review & editing.

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## APPENDIX

Table A1. Case study protocol.

Source 1. Face-to-face interviews	
General overview	Introduction about the informant's experience and role in the company and S&OP. Description of the company's ETO product families.
S&OP process	Description of each S&OP step and underlying activity: Demand planning: Product portfolio planning, data gathering, forecasting, and demand review (assumption tracking and risk management) Supply planning: Capacity (including engineering) planning, production planning, and supply chain planning Pre-S&OP executive: Financial planning and meeting S&OP executive meeting Describe the activities' sequence, interacting entities (participants and information systems), inputs and how they are received and utilised, and outcomes and how they are communicated and utilised within and outside the S&OP. For each meeting with S&OP, describe the agenda, duration, participants, review routines, inputs, and outcomes.
S&OP setup and maturity	Describe the S&OP setup (frequency, focus) and the changes in the S&OP implementation maturity since the last assessment.
S&OP integration with other processes	Describe other processes with which S&OP interacts. Medium of interaction: Face-to-face or distanced interfaces, information system platforms: How are reciprocations of inputs and outcomes between processes conducted? Integrated points (S&OP steps and activities): Where in the S&OP process do the other processes' outcomes enter as inputs? Where do the S&OP process outcomes enter as inputs to the other processes? Interacting entities: Participants and information systems between the processes Inputs from S&OP and how inputs are received and utilised Outcomes to S&OP and how outcomes are communicated and utilised in S&OP
Decoupling position	Referring to ETO product families: What are the engineering and production activities performed before and after the entry of customer orders?
Drivers of ETO uncertainty and equivocality	Describe the areas of demand- and supply-related uncertainty that S&OP deals with concerning ETO-product families. What drivers of uncertainty associated with engineering changes originate from demand, product, production, process, and engineering capacity? Describe your opinion concerning each driver and how the changes increase related uncertainty.
Demand-supply balancing	Describe how S&OP affected performance in engineering utilisation and delays over the last three years, sales loss due to engineering capacity constraints, and perfect order fulfilment.
S&OP's information processing performance requirements	Describe the information processing requirements generated by the information processing requirements your S&OP necessitates to meet: Informational quality: e.g. forecast accuracy, timely visualisation of problems, identification of bottlenecks outside the most extended supply lead-time, information about new product introductions, and inventory-related information. Procedural quality: e.g. ability to perform what-if modelling and scenario-based decisions to optimise demand and supply planning using valid inference rules to estimate future demand and supply capacity needs. Alignment quality: e.g. horizontal alignment (goals and decisions of demand and supply functions), vertical alignment (operational goals contribute to the company's growth and product innovation plans and other long-term objectives and decisions), proactivity instead of reactivity. Constructive engagement: e.g. feedback from functional areas, coordination (e.g. executive support and cross-functional teaming), collaborative culture.
Source 2. Direct observations	
Joint meetings	Additional notes about discussions between informants during joint interviews
Demo sessions	Presentations of internal systems (e.g. ERP and planning software) supporting data collection, processing, and transmitting within forecasting, S&OP, capacity planning, engineering activities, tendering, and project management.
Source 3. Publicly available documents	
Company's website	General introduction about the company: industry, product portfolio, strategy, mission, history, descriptions of products and solutions (e.g. product range, technical characteristics, machine performance, product comparison).
Annual report 2019	Turnover, employees, recent technology launches, new markets, yearly evaluations
Source 4. Internal documents	
Digital or paper materials	Detailed process descriptions and maps of S&OP, forecasting, capacity planning, tendering, product portfolio management, product life cycle management, project management, and other supporting documents that directly relate to the study's constructs/variables: e.g. most recent S&OP maturity assessments, previous meeting agendas and minutes, reports about delays and deviations vis-à-vis planned vs. reported engineering hours from earlier projects over the last three years, reports about rejected orders due to lack of capacity.

**Table A2.** Aggregate sources of uncertainty.

Source of uncertainty	Corresponding information category	Description
Supply chain volatility	Technical specifications, overall product customisability	Volatility stems from variability in technical specifications and the degree of product customisation.
Demand fluctuation	Number of units per order, sales process revenue	The custom nature of each ETO project influences the number of units per order and potential sales revenue.
Technological changes	Overall product customisability, customisable systems per product	Rapid technological changes can influence the level of product customisability and the number of customisable systems per product.
Project complexity	Technical specifications, overall product customisability, customisable systems per product, production capacity flexibility	The complexity of each ETO project is influenced by these categories, affecting specifications, customisability, and production capacity.
Market competition	Sales process revenue, budget per order, technical specifications	Market competition affects the probability of winning orders, the budget requirements for each order, and the complexity of technical specifications.
Regulatory changes	Production layout, machine productivity, external labour/subcontractors	Regulatory changes can impact the stability of production layouts, machine efficiency, and availability of skills and expertise outside the firm.
Geopolitical factors	External labour/subcontractors, subcontracting cost	Changes in geopolitical scenarios can affect the availability and cost of external resources.
Resource availability	Internal labour availability, labour productivity, inter-resource equivalences	Changes in resource availability and allocation affect labour availability, productivity, and possibilities for labour substitution.

**Table A3.** Aggregate sources of equivocality.

Source of equivocality	Corresponding information Category	Description
Complexity of requirements	Technical specifications, overall product customisability	Technical specifications and product customisability directly influence the complexity of project requirements in ETO operations. The more variability and customisation, the higher the complexity and potential equivocality.
Technological unpredictability	Technical specifications, customisable systems per product	New and cutting-edge technologies often have to be incorporated into ETO products. This process can lead to multiple interpretations and understanding, causing equivocality.
Interdepartmental dependencies	Overall product customisability, production capacity flexibility, inter-resource equivalences	Due to their unique, custom nature, cross-departmental dependencies and collaboration are critical in ETO operations. This complexity can lead to multiple interpretations and understandings of roles, tasks, and processes, causing equivocality.
Supplier-related equivocality	Setup cost, minimum inbound inventory, external labour/subcontractors, subcontracting cost	Variability in supplier performance and high dependence on suppliers for ETO operations can introduce uncertainty, leading to multiple potential outcomes and equivocality.
Tacit knowledge	Labour skill development pace, labour type, internal labour availability, labour productivity	ETO operations often rely on the tacit knowledge of their personnel. If not shared or documented, this knowledge can lead to multiple interpretations or understandings, causing equivocality.
Regulatory ambiguity	Production layout, machine productivity, external labour/subcontractors	Unclear or changing regulatory environments can introduce high equivocality. The necessary adaptations in the production process or layout, machine productivity, and engagement of external resources can lead to multiple interpretations.
Market dynamics	Number of units per order, sales process revenue, budget per order	Market dynamics influence the variability of the number of units per order, revenue, and budget. Fluctuations in these aspects can lead to multiple interpretations and complexities in managing ETO operations.
Contractual complexity	Number of units per order, sales process revenue, budget per order	Complex contracts with varied terms can affect the number of units per order, revenue, and budget, thereby leading to multiple interpretations and complexities in managing ETO operations.
Workforce dynamics	Labour skill development pace, labour type, internal labour availability, labour productivity, inter-resource equivalences	The complexity of workforce tasks and skills introduces ambiguities and multiple interpretations concerning skill classification, task design, skill equivalences, and substitutability, further contributing to equivocality.
Communication barriers	Overall product customisability, production capacity flexibility, inter-resource equivalences	Miscommunication or lack of effective communication can lead to varied interpretations of product customisation, production capacity flexibility, and inter-resource equivalences, thereby contributing to equivocality.

Table A4. IPRs and links to S&OP quality requirements and IPC-building strategies.

IPR	Cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies	Description
1.1 Order size forecasting	Case A demonstrates a fit with its customer monitoring teams that continuously collect and analyse relevant data. Cases B, C, and D exhibit misfits due to the absence of explicit forecasting mechanisms.	IQ: The misfits in B, C, and D stem from a lack of formal mechanisms to collect and organise the data needed for accurate forecasting, directly impacting Informational Quality. A's fit demonstrates effective data management. PQ: The universal misfit highlights the absence of methodologies to manage the uncertainty of variable order sizes, a key aspect of Procedural Quality. No case has implemented the necessary analytical tools.	1. Dedicated customer monitoring systems 2. Configurational impact simulation systems	Implementation of teams and systems specifically designed to collect, analyse, and report on order size patterns and fluctuations. Addresses the misfits in B, C, and D by providing the missing data collection mechanism (IQ). Development of modelling tools that quantify how order size variations affect capacity, production, and inventory. Addresses the universal misfit by providing a methodology to manage uncertainty (PQ).
1.2 Order-size impact sensitivity analysis	All cases (A, B, C, and D) demonstrate a misfit. While Cases A and B acknowledge the need for order-size impact estimations, no case shows explicit implementation of formal analytical tools to address the configurational adjustments needed due to order-size variability.	IQ & CE: The fit across A, B, and C demonstrates the successful communication between departments (AQ) and integration of diverse expertise (CE) through structured S&OP interaction. IQ & PQ: A's fit comes from systematic data collection (IQ) and a process for managing uncertainty in sales (PQ). B's partial fit lacks the procedural refinement. Low hit rates in the cases indicate deficiencies in both areas.	3. Cross-functional validation frameworks 4. Integrated hit-rate forecasting and feedback systems	Establishment of S&OP forums with protocols to review and challenge order size assumptions. Leverages the existing fit in A, B, and C, further strengthening communication (AQ) and diverse expertise (CE). Systems that track tender status and refine hit-rate predictions. Builds on A's fit and B's partial fit by adding the crucial element of continuous refinement (PQ), improving data collection (IQ).
1.3 Shared understanding of order size variability assumptions	Cases A, B, and C demonstrate a fit due to their intensification of cross-functional validation within S&OP, involving relevant participants and dedicated meeting protocols.	AQ & CE: The fit across A, B, and C demonstrates the successful communication between departments (AQ) and integration of diverse expertise (CE) through structured S&OP interaction. IQ & PQ: A's fit comes from systematic data collection (IQ) and a process for managing uncertainty in sales (PQ). B's partial fit lacks the procedural refinement. Low hit rates in the cases indicate deficiencies in both areas.	5. Centralised market knowledge repositories with formalised validation forums 6. Contractual and budget flexibility frameworks / Budget flexibility frameworks	Formal process for collecting, analysing, and disseminating market knowledge. Extends C's fit by establishing a dedicated resource, addressing the implied misfits in other cases (IQ and CE). Contractual: Establishment of contract terms allowing budget adjustments. Budget: Mechanisms for adjusting budgets. Addresses A's partial fit by adding formal mechanisms (PQ) and ensuring alignment (AQ).
1.4 Robust hit-rate forecasting	Case A demonstrates a fit with integrated forecasting and feedback systems, continuously refined through customer interaction. Case B shows a partial fit with a tracking system, but lacks hit rate updates. Cases C and D are not explicitly addressed, but implied misfits.	IQ & CE: C's fit highlights the effective organised collection of market data (IQ) and the use of forums for collaborative interpretation (CE). Other cases are implied misfits due to lack of this structure. PQ & AQ: A's partial fit demonstrates an understanding of needing to manage uncertainty (PQ) in budgeting, but lacks formal mechanisms. The misfits across other cases lack both the methods and the alignment between project changes and finances (AQ).	7. Cost driver tracking and review 8. Resource-constrained scenario planning/Multi-dimensional resource-budget simulation tools	System for tracking cost drivers and reviewing assumptions. Leverages C's fit by broadening the scope to all cost assumptions, addressing implied misfits in other cases (IQ and PQ). Planning: collaborative process to create scenarios outlining the future state. Tools: modelling capabilities to simulate the impact of budget decisions. Addresses the needs outlined in D and B (partial fit), adding integrated resource considerations (PQ and CE).
1.5 Competitive and market intelligence integration	Case C demonstrates a fit by combining a 'Sales Force' knowledge repository with regular regional validation meetings. Cases A, B, and D are not explicitly addressed but implied misfits.	IQ & PQ: C's fit shows effective collection and organisation of cost data (IQ) and a defined process for validation (PQ). Other implied misfits lack these data systems.	9. Real-time budget monitoring and alerting / Proactive budget deviation detection systems	Monitoring: System that tracks spending against planned budgets. Detection: monitoring systems with predefined thresholds. Extends C's partial fit by adding proactive, automated
2.1 Dynamic adjustments of budgets	Case A demonstrates a partial fit with 10-20% contract flexibility, showing awareness but potentially lacking formal mechanisms. Cases B, C, and D exhibit misfits due to limited visibility and predictability in budgeting.	PQ & CE: D's recognition of the need represents a misfit, while B's configurator tools are a partial fit. This demonstrates the need for methods to manage uncertainty in resource allocation (PQ) and tools for integrating diverse expertise (CE). IQ & PQ: C's partial fit shows an understanding of the need for budget information to support timely decision-making (IQ) and proactive methods for capturing variance (PQ). Other cases are implied misfits.		
2.2 Dynamic validation of cost assumptions	Case C demonstrates a fit by implementing cost tracking and cost change impact analysis to accommodate potential cost fluctuations. Cases A, B and D are not explicitly addressed, but implied misfits.			
2.3 Integrated scenario planning for budget-resource alignment	Case D recognises the need (misfit), and Case B uses configurator tools (partial fit), representing a partial fit due to improved initial cost estimation, but lacking fully integrated resource considerations. Cases A and C have no explicit mention (misfit).			
2.4 Early warning for budget deviations	Case C demonstrates a partial fit with a built-in early warning system as part of their cost-tracking systems. Cases A, B, and D have no explicit mention (misfit).			

(continued)

Table A4. Continued.

IPR	Cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies	Description
3.1 Structured categorisation of specifications	Cases A, B, and C demonstrate a fit by employing progressive specification development frameworks and categorising specifications. Case D shows a misfit.	IQ & PQ: A, B, and C's fit demonstrates the value of organising specification data (IQ) and establishing consistent handling methods (PQ). D's misfit lacks these structured approaches.	10. Specification taxonomy and classification	detection, addressing implied misfits (IQ and PQ). Develop a standardised taxonomy for categorising specifications. Maintains the fit in A, B, and C, addressing D's misfit by providing a structured approach (IQ and PQ).
3.2 Systematic documentation of specification evolution	Case A indicates a fit with documented specification evolution patterns, though the level of formality is unclear. Cases B, C and D are not explicitly addressed, but implied misfits.	IQ: A's fit (though formality is unclear) demonstrates the need for collecting and organising evolving specification data to support decision-making. Other cases implied misfits lack this information management.	11. Implement a centralised, version-controlled specification management system	Engineering change management system to document and track changes to specifications. Formalises A's fit (where formality was unclear) and addresses implied misfits by improving information management (IQ).
3.3 Real-time communication between sales and engineering	Case D highlights a misfit due to its need for real-time communication channels, stemming from broader specification ranges and higher initial uncertainty. Cases A, B and C are not explicitly addressed, but implied misfits.	AQ & CE: D's misfit stems from a lack of communication between departments (AQ) and a failure to integrate diverse expertise (CE) in the specification process.	12. Cross-functional specification refinement platforms	Shared digital platform facilitating real-time communication. Directly addresses D's misfit by enabling communication (AQ) and integrating expertise (CE).
3.4 Customisation scope definition	Cases B and D demonstrate a fit with structured modularity frameworks. Case C shows a partial fit with application specialists operating within defined boundaries but with some flexibility. Case A exhibits a misfit with its "case-by-case" approach.	PQ & AQ: B and D's fit shows the value of establishing clear guidelines (PQ) and defining boundaries (AQ) for customisation. C's partial fit has some structure. A's misfit lacks formalisation.	13. Modular boundaries system with knowledge integration platforms	Formalised system defining customisation options and rules. Builds on the fit in B and D and the partial fit in C, providing the formalisation A lacks (PQ and AQ).
3.5 Design feasibility assessment	Cases B and D demonstrate a fit with simplified feasibility assessment. Case C shows a partial fit, balancing pre-defined options with expert judgement. Case A exhibits a misfit with an unstructured "case-by-case" assessment.	PQ & CE: B and D's fit again highlights structured methods (PQ). C's partial fit uses both structured information and expert judgement. A's misfit stems from a lack of structured methods and integrated expertise (CE).	14. Multi-level feasibility assessment framework	Formal framework for evaluating designs, with cross-functional reviews. Extends the fit in B and D and the partial fit in C, adding structure and integration of expertise (PQ and CE) where A is lacking.
3.6 System interdependency mapping	Case B demonstrates a fit with sophisticated multi-level configuration management systems. Case C shows a partial fit with simpler approaches. Cases A and D exhibit misfits due to the lack of structured approaches.	IQ & PQ: B's fit shows effective collection and organisation of interdependency data (IQ) and methods to manage uncertainty (PQ). C's partial fit has simpler approaches. A & D's misfits lack structured documentation.	15. Multi-level dependency modelling and visualisation	System to document interdependencies. Builds on B's fit and C's partial fit, providing a formal system for A and D (PQ and IQ).
3.7 Configuration tracking and version control	Case B demonstrates a fit with sophisticated multi-level configuration management systems. Case C shows a partial fit with a combination of formal and informal methods. Cases A and D exhibit misfits due to the lack of adaptive tracking systems.	IQ & PQ: B's fit highlights the need for collecting and organising configuration data (IQ) and managing uncertainty (PQ) in complex systems. C's partial fit uses a combination of methods. A and D's misfits lack these systems.	16. Complexity-adaptive configuration management system	System to track configurations, adapting to complexity. Extends B's fit and C's partial fit, providing a scalable solution where A and D are lacking (IQ and PQ).
3.8 Compatibility validation	Case B demonstrates a fit with a system for validating compatibility. Case C suggests a partial fit with progressive validation processes, but relies more on manual checks. Cases A and D exhibit misfits due to the lack of automated checks.	PQ & CE: B's fit comes from methods to identify and address compatibility issues (PQ). C's partial fit uses manual checks. A & D's misfits lack integrated expertise (CE) in validation.	17. Progressive and automated compatibility validation	System to check for compatibility issues. Builds on B's fit and C's partial fit, adding automation and progression, addressing implied misfits in A and D (PQ and CE).
4.1 Rapid layout reconfiguration planning	Case A demonstrates a partial fit by recognising the need for dynamic layout simulation, but lacks full implementation. Cases B, C, and D show misfits with no explicit reconfiguration planning approaches.	PQ & CE: A's partial fit recognises the need for methods enabling rapid iteration (PQ) but lacks full implementation. B, C, and D's misfits stem from a lack of integrated production expertise (CE) in planning.	18. Dynamic production layout simulation and optimisation	Simulation tools for layout prototyping. Addresses A's partial fit (adding full implementation) and the misfits in B, C, and D by providing a rapid iteration capability (PQ and CE).

(continued)

Table A4. Continued.

IPR	Cross-case IPR-IPC fit/misfit	S&OP quality	IPB-building strategies	Description
4.2 Real-time layout performance monitoring	Cases B, C, and D show partial fits by recognising the need for real-time monitoring, but lack full implementation. Cases A is not explicitly addressed, but implied a misfit.	IQ & AQ: B, C, and D's partial fits show a need for performance data to support rapid decisions (IQ), but lack full implementation. The lack of a shared view (AQ) hinders communication. A is not explicitly addressed, but implied a misfit. PQ: A's fit demonstrates the need for methods to manage uncertainty (PQ) in layout changes. Other cases are implied misfits due to lack of analytical tools.	19. Real-time layout performance monitoring and disruption detection system	System using sensors and analytics to monitor KPIs. Builds on the partial fits in B, C, and D, adding full implementation and addressing the implied misfit in A (IQ and AQ).
4.3 Layout change impact analysis	Case A demonstrates a fit with sophisticated tools for layout change impact analysis. Cases B, C and D are not explicitly addressed, but implied misfits.	IQ & PQ: A's fit comes from using data for data-driven assessment (IQ) and structured analysis (PQ). C and D's partial misfits recognise the need but lack robust methods. B is an implied misfit due to limited visibility.	20. Integrated layout change impact assessment tools	Impact assessment tools integrated with layout software. Formalises and extends A's fit, addressing implied misfits in other cases (PQ).
4.4 Current capacity assessment	Case A demonstrates a fit with advanced simulation and modelling tools. Cases C and D show partial misfits due to needing more robust assessment methods. Case B is not explicitly addressed, but implied a misfit.	PQ & AQ: A's fit stems from using tools to manage uncertainty (PQ) in planning. D's partial fit recognises the need. B and C's misfits lack the alignment (AQ) between capacity constraints and planning decisions.	21. Multi-parameter capacity modelling and analysis system	System for assessing capacity across multiple dimensions. Builds on A's fit and addresses the partial misfits in C and D, adding comprehensiveness and addressing B's implied misfit (IQ and PQ).
4.5 Capacity change impact prediction	Case A demonstrates a fit with tools to predict the impact of changes. Case D shows a partial fit by recognising the need. Cases B and C show misfits with limited impact prediction capabilities.	IQ: A, B, and C's partial fits show a need for deviation data to support timely intervention (IQ), but lack full implementation. D is an implied misfit due to lack of systems.	22. Predictive capacity planning with scenario modelling	Scenario modelling to forecast impacts of changes. Extends A's fit and D's partial fit, addressing the misfits in B and C by providing a predictive capability (PQ and AQ).
4.6 Real-time process deviation monitoring	Cases A, B, and C show partial fits by recognising the need, but lacking full implementation. Case D is not explicitly addressed, but implied a misfit.	IQ: A, B, and C's partial fits show a need for deviation data to support timely intervention (IQ), but lack full implementation. D is an implied misfit due to lack of systems.	23. Real-time SPC and deviation alerting system	System using SPC and alerts for deviations. Builds on the partial fits in A, B, and C, providing full implementation and addressing the implied misfit in D (IQ).
4.7 Real-time machine performance tracking	Cases C and D show partial fits by recognising the need. Case A demonstrates a fit with integrated tracking frameworks. Case B is not explicitly addressed, but implied a misfit.	IQ & PQ: C and D's partial fits and A's fit demonstrate a need for collecting performance data (IQ) and methods to understand capabilities (PQ). B is an implied misfit due to lack of frameworks.	24. Machine-level data acquisition and predictive analytics for material-machine interaction	System using sensors and analytics for machine performance. Extends A's fit and the partial fits in C and D, adding predictive capabilities and addressing B's implied misfit (IQ and PQ).
4.8 Root cause analysis of quality issues	Cases A, B, and C show partial fits by recognising the need, but lacking full implementation. Cases D is not explicitly addressed, but implied a misfit.	PQ, IQ & CE: A, B, and C's partial fits recognise the need, but lack full implementation. Full implementation requires approaches to identify causes of problems (PQ), organise solution data (IQ) and integrate diverse expertise (CE).	25. Structured root cause analysis with knowledge sharing	RCA methodology and tools with knowledge sharing. Builds on the partial fits in A, B, and C, adding structure and addressing the implied misfit in D (PQ, IQ, and CE).
4.9 Root cause analysis for performance deviations	Cases C and D show partial fits by recognising the need. Case A demonstrates a fit by linking machine condition to output. Case B is not explicitly addressed, but implied a misfit.	IQ, PQ & CE: C and D's partial fits and A's fit show the value of integrated data (IQ), methods to address performance uncertainty (PQ), and integrating diverse expertise (CE). B is an implied misfit.	26. Integrated root cause analysis for performance with condition-performance correlation	RCA methodology integrating data from multiple sources. Extends A's fit and the partial fits in C and D, addressing B's implied misfit by adding data integration and broader scope (IQ, PQ, and CE).
4.10 Contingency planning	Case A demonstrates a fit with advanced simulation tools and research initiatives for contingency planning. Case C shows a partial fit by recognising the need. Cases B and D are not explicitly addressed, but implied misfits.	PQ & AQ: A's fit uses methods to proactively manage uncertainty (PQ). C's partial fit recognises the need. B and D are implied misfits, lacking alignment (AQ) in understanding constraints and disruptions.	27. Scenario-based contingency planning with simulation-based evaluation	System using scenario planning and simulation. Builds on A's fit and C's partial fit, adding simulation and addressing implied misfits in B and D (PQ and AQ).
4.11 Setup cost modelling	Case A demonstrates a fit with predictive cost modelling systems. Case C shows a partial misfit with historical data usage but not in S&OP. Case D is a potential misfit, relying on experience. Case B is not explicitly addressed, but implied a misfit.	IQ & PQ: A's fit stems from using data-driven cost data (IQ) and methods to predict setup costs (PQ). C's partial misfit lacks S&OP integration. D's potential misfit relies on experience. B is an implied misfit.	28. Activity-based predictive setup cost modelling	System combining ABC and predictive modelling. Builds on A's fit, addressing C's partial misfit and the potential misfit in D, and B implied misfit by adding activity-based detail and prediction (PQ and IQ).

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Table A4. Continued.

IPR	Cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies	Description
4.1.2 Setup cost data integration	All cases (A, B, C, and D) demonstrate misfits due to the separation between cost modelling and S&OP.	IQ & AQ: All cases' misfits show a need for presenting cost data accessibly (IQ) and facilitating communication (AQ) about cost constraints. IQ & PQ: All cases' misfits stem from a need to organise competency data (IQ) and support structured analysis (PQ) for workforce planning.	29. Cross-functional setup cost integration with S&OP	System integrating setup cost data into S&OP. Directly addresses the misfits in all cases by ensuring setup costs are considered in planning (IQ and AQ).
5.1 Competency mapping	All cases (A, B, C and D) are a clear misfit, needing improved competency mapping.	IQ & PQ: All cases' misfits stem from a need to organise competency data (IQ) and support structured analysis (PQ) for workforce planning.	30. Competency taxonomy and skills inventory system	System for defining, tracking, and managing skills. Directly addresses the misfits in all cases by providing a structured framework for competency data (IQ and PQ).
5.2 Learning curve prediction	All cases (A, B, and C) demonstrate misfits due to difficulties in predicting learning curves and a lack of effective systems. Case D is not explicitly addressed, but implied a misfit.	PQ & IQ: All cases' misfits point to a need for methods of predictive modelling (PQ) for workforce development, using historical data (IQ).	31. Skill development trajectory modelling	System using learning curve models. Directly addresses the misfits in all cases by providing a predictive capability for skill acquisition (PQ and IQ).
5.3 Skill-gap forecasting	All cases (A, B, and C) demonstrate misfits due to limitations in proactive skill-gap forecasting. Case D is not explicitly addressed, but implied a misfit.	PQ & AQ: All cases' misfits highlight the need for methods to manage uncertainty (PQ) in future workforce requirements and ensure alignment (AQ) in understanding skill constraints.	32. Proactive skill gap analysis and forecasting	System for assessing current vs. future skill needs. Directly addresses the misfits in all cases by providing a proactive, forward-looking analysis (PQ and AQ).
5.4 Dynamic skill profiling	All cases (A, B, C, and D) demonstrate misfits due to limitations in dynamic skill profiling.	IQ & AQ: All cases' misfits stem from a need for collecting and organising current capability data (IQ) and maintaining alignment (AQ) between skills and needs.	33. Real-time skill and capability tracking system	System for updating skill profiles and workloads. Directly addresses the misfits in all cases by maintaining current and accurate capability data (IQ and AQ).
5.5 Skill-based task analysis	Case C demonstrates a misfit due to a lack of formal methods. Case B shows a partial fit with team manager validation but lacks granular analysis. Cases A and D exhibit misfits due to the lack of structured approaches.	PQ & CE: C's misfit and B's partial fit highlight the need for methods to identify skill requirements (PQ) and integrate diverse expertise (CE) in task analysis. A and D are misfits.	34. Task-skill decomposition and requirement specification	Process for mapping tasks to required skills. Addresses C's misfit and B's partial fit, providing a structured approach where A and D are lacking (PQ and CE).
5.6 Predictive workload allocation	Cases A and D demonstrate fits with structured approaches. Cases B and C exhibit misfits due to a lack of integration with S&OP and failure to proactively address skill shortages.	PQ, AQ & CE: A and D's fits stem from methods linking skills, availability, and needs (PQ) and ensuring workload understanding (AQ). B and C's misfits lack this integration, limiting constructive engagement (CE).	35. Skills-based resource allocation and workload balancing system	System for allocating workloads based on skills and balance. Builds on the fits in A and D, addressing the misfits in B and C by adding predictive allocation and integration with S&OP (PQ, AQ & CE).
5.7 Centralised availability tracking	All cases (A, B, C, and D) demonstrate misfits due to fragmented availability information.	IQ: All cases' misfits stem from a need to collect and organise availability data as a single source of truth (IQ).	36. Enterprise-wide unified availability management system	System consolidating availability information. Directly addresses the misfits in all cases by providing a single source of truth for availability (IQ).
5.8 Role-specific availability views	All cases (A, B, C, and D) demonstrate misfits with limited evidence of customised availability views. Case B shows the most severe misfit with restricted access.	IQ & AQ: All cases' misfits highlight a need for presenting data to support role-specific decisions (IQ) and facilitating communication (AQ) about constraints.	37. Role-customised availability dashboards and interfaces	System providing tailored views of availability. Directly addresses the misfits in all cases (most severe in B) by providing role-specific information (IQ and AQ).
5.9 S&OP availability integration	All cases (A, B, C, and D) demonstrate misfits due to a disconnect between detailed planning and S&OP.	AQ & CE: All cases' misfits result from a need to facilitate communication about availability constraints (AQ) and integrate diverse expertise (CE) in capacity planning.	38. Workforce availability integration with S&OP	System integrating availability data into S&OP. Directly addresses the misfits in all cases by ensuring availability is considered in strategic planning (AQ and CE).
5.10 Unified productivity tracking	Case B demonstrates a partial fit with established skill matrices. Cases A, C, and D exhibit misfits due to a lack of systematic data collection.	IQ & PQ: B's partial fit has some structure, but A, C, and D's misfits point to a need for collecting and organising productivity data (IQ) and methods to measure and analyse productivity (PQ).	39. Centralised time tracking for productivity measurement	System tracking time spent on projects and tasks. Builds on B's partial fit, addressing the misfits in A, C, and D by providing systematic data collection (IQ and PQ).
5.11 Skill-based performance analysis	All cases (A, B, C, and D) demonstrate misfits with limited explicit connection between skill profiles and performance outcomes.	PQ: All cases' misfits stem from a need for methods to analyse performance variations (PQ) by linking metrics to skills.	40. Competency-based performance analysis	System linking performance metrics to skills. Directly addresses the misfits in all cases by enabling analysis of skill-performance relationships (PQ).

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Table A4. Continued.

IPR	Cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies	Description
5.12 Integrated productivity forecasting	All cases demonstrate a general misfit due to difficulty in predicting learning curves and limitations in productivity tracking.	PQ: All cases' general misfit highlights a need for methods to predict productivity (PQ).	41. Productivity forecasting with historical data and skill integration	Forecasting models using historical data and skills. Directly addresses the general misfit across cases by providing a predictive capability for productivity (PQ).
5.13 Substitution rule documentation	All cases (A, B, C, and D) demonstrate misfits with limited formalisation of substitution rules.	IQ, AQ & PQ: All cases' misfits point to the need for organising substitution rules (IQ), facilitating communication about options (AQ), and having clear rules governing substitutions (PQ).	42. Formalised substitution rule repository and governance system	Repository documenting substitution rules. Directly addresses the misfits in all cases by providing a formalised, accessible system for substitution rules (IQ, AQ & PQ).
5.14 Skill-based substitution mapping	All cases (A, B, C, and D) demonstrate the same misfits as IPR 42.	PQ: All cases' misfits (same as IPR 42) stem from a need for methods to identify and evaluate potential substitutions based on objective skill criteria (PQ).	43. Competency-based substitution matrix and equivalence framework	System for identifying substitutes based on skills. Directly addresses the misfits in all cases (same as 5.13) by providing a skill-based approach to substitution (PQ).
5.15 Cross-functional substitution coordination	Case B shows a partial fit with interdepartmental liaison roles, but inconsistency suggests a need for formalisation. Case C demonstrates a misfit, relying on personal experience. Cases A and D are not explicitly addressed, but implied misfits.	AQ & CE: B's partial fit needs more formalisation. C's misfit highlights a need for communication about substitution options (AQ) and integrating diverse perspectives (CE). A and D are implied misfits.	44. Formalised interdepartmental substitution process and platform	System for coordinating substitutions across departments. Builds on B's partial fit, addressing C's misfit and the implied misfits in A and D by formalising the process (AQ and CE).
6.1 Demand signal processing for custom materials	Case B exhibits a partial fit with complex algorithms but high stockout/obsolescence. Cases C and D demonstrate misfits with similar issues and a lack of specific safety stock discussions. Case A is not explicitly addressed, but implied a misfit.	IQ & PQ: B's partial fit uses algorithms but needs improvement. C and D's misfits show a need for structured conversion of requirements into demand signals (IQ) and methodologies to quantify uncertainty (PQ). A is a misfit.	45. Adaptive forecasting for custom material demand	Forecasting algorithms addressing custom materials. Builds on B's partial fit, addressing the misfits in C and D, and implied misfits in A by providing specialised forecasting for custom materials (PQ and IQ).
6.2 Real-time tracking of customised inventory	Cases B and D show partial fits with some monitoring and supplier access. Case C exhibits a misfit with reactive reporting. Case A is not explicitly addressed, but implied a misfit.	IQ & AQ: B and D's partial fits have some monitoring, but need more integration. C's misfit highlights a need for real-time data to support intervention decisions (IQ) and shared understanding of constraints (AQ). A is a misfit.	46. Real-time custom material tracking	System providing a view of custom inventory. Builds on the partial fits in B and D, addressing C's misfit and the implied misfits in A by adding real-time tracking and differentiated alerting (IQ and AQ).
6.3 Integrated make-or-buy analysis	Case A demonstrates a fit with make-or-buy analysis integrated into early S&OP steps. Cases C and D exhibit misfits with a lack of formal analysis within S&OP. Case B is not explicitly addressed, but implied a misfit.	PQ, CE & AQ: A's fit demonstrates consistent methodologies for evaluating sourcing options (PQ) and incorporating diverse perspectives (CE), while ensuring alignment (AQ) with capabilities. C and D's misfits lack this formalisation.	47. Cross-functional make-or-buy decision framework for S&OP	Framework for evaluating sourcing options. Builds on A's fit, addressing the misfits in C and D and the implied misfits in B by formalising the process and integrating it with S&OP (PQ, CE, and AQ).
6.4 Proactive sourcing and vetting	Case A demonstrates a partial fit with an organisational development program tracking external skills. Cases C and D exhibit misfits due to reactive approaches. Case B is not explicitly addressed, but implied a misfit.	PQ & IQ: A's partial fit proactively tracks skills. C and D's misfits show a need for methodologies to proactively evaluate resources (PQ) and structured repositories of supplier capabilities (IQ). B is an implied misfit.	48. Proactive supplier qualification and relationship management	System for evaluating and pre-approving suppliers. Builds on A's partial fit, addressing the misfits in C and D and the implied misfits in B by adding proactive qualification and relationship management (PQ and IQ).
6.5 External resource pool profiling	Case A demonstrates a partial fit with tracking of external skills, but lacks comprehensive profiling. Cases C and D show severe misfits with fragmented, ad-hoc knowledge. Case B is not explicitly addressed, but implied a misfit.	IQ: A's partial fit tracks skills, but lacks comprehensive profiling. C and D's severe misfits stem from a need for organised external capability data (IQ). B is an implied misfit.	49. Subcontractor database and capability matrix	Repository of subcontractor information. Builds on A's partial fit, addressing the severe misfits in C and D and the implied misfits in B by providing a structured database of subcontractor capabilities (IQ).

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Table A4. Continued.

IPR	Cross-case IPR-IPC fit/misfit	S&OP quality	IPC-building strategies	Description
6.6 Subcontracting cost driver analysis	Case D exhibits a misfit with no specific cost management strategies. Case C shows a similar misfit, relying on informal methods. Case B demonstrates a partial fit with extensive data collection. Case A is not explicitly addressed, but implied a misfit.	PQ: D and C's misfits and B's partial fit show a need for methodologies to identify and analyse cost variation patterns (PQ). A is an implied misfit.	50. Subcontracting cost driver analysis and variability modelling	System for analysing subcontracting cost drivers. Addresses the misfits in D and C and B's partial fit by providing a deeper understanding of cost variation (PQ).
6.7 Dynamic cost forecasting	Cases C and D exhibit misfits with no cost change prediction capability. Case B shows a partial fit with some cost stability but limited forecasting. Case A is not explicitly addressed, but implied a misfit.	PQ: C and D's misfits and B's partial fit stem from a need for methods to predict and manage uncertainty (PQ) in costs. A is an implied misfit.	51. Market-sensitive subcontracting cost forecasting	Forecasting model incorporating market factors. Addresses the misfits in C and D and B's partial fit by adding a predictive, market-sensitive capability (PQ).
6.8 Strategic sourcing alignment	Case B demonstrates a partial fit with a three-level allocation system and competency delineation. Cases C and D exhibit misfits with no strategic sourcing alignment. Case A is not explicitly addressed, but implied a misfit.	AQ: B's partial fit shows some competency delineation. C and D's misfits highlight a need to ensure subcontracting decisions support strategic objectives (AQ). A is an implied misfit.	52. Strategic sourcing integration with S&OP for competency development	System integrating sourcing strategy with S&OP. Builds on B's partial fit, addressing the misfits in C and D and the implied misfits in A, ensuring alignment with strategic objectives (AQ).

Note. - A, B, C, D: The cases in the multiple-case study where the IPC strategies were identified.

IQ: Informational Quality; PQ: Procedural Quality; AQ: Alignment Quality; CE: Constructive Engagement.

Table A5. First- and second-order IPC-building strategies supporting ETO S&OP process and decisions.

S&OP process step	First-order IPC-building strategies	Description	Second-order IPC-building strategies	Supported S&OP decisions
Demand review	Demand signal and market intelligence platform	Centralised system integrating hit-rate forecasting, competitive intelligence, and order pattern analysis. Provides systematic collection, analysis, and dissemination of market knowledge within the S&OP process.	1, 4, 5	Hit-rate prediction refinement Competitive landscape assessment
	Order-size impact analysis toolkit	Modelling tools that quantify how order size variations affect capacity, production scheduling, and inventory allocations across concurrent projects. Includes cross-functional validation frameworks for reviewing underlying assumptions.	2, 3	Capacity adjustment determinations Concurrent project impact assessment
	Financial planning integration platform	Framework for budget flexibility, cost tracking, and scenario modelling. Includes contract terms allowing budget adjustments, tracking of key cost drivers, and mechanisms for detecting budget deviations against predefined thresholds.	6a, 6b, 7, 8a, 8b, 9a, 9b	Budget allocation across projects Cost variance threshold definitions
Supply review	Specification management and feasibility system	Comprehensive system for categorising customer requirements and technical specifications with standardised taxonomy, version control, and cross-functional communication platforms. Includes structured frameworks for evaluating design feasibility and compatibility.	10, 11, 12, 13, 14, 15, 16, 17	Customisation boundary determinations Technical feasibility confirmations
	Production system configuration framework	Tools for rapid prototyping, evaluation, and optimisation of production layout configurations. Includes simulation capabilities, real-time monitoring with sensor networks, and impact assessment for proposed layout changes.	18, 19, 20	Material flow optimisation Layout change implementation scheduling
	Capacity planning and analysis workbook	Multi-parameter modelling and analysis system that quantifies capacity across machine availability, labour resources, space constraints, and process bottlenecks. Includes scenario modelling tools to forecast impacts of capacity changes.	21, 22	Machine allocation priorities Bottleneck mitigation actions
	Integrated production monitoring and control	Real-time Statistical Process Control (SPC) system with sensors and analytical tools to detect process deviations. Includes structured methodologies for root cause analysis of quality issues and performance deviations.	23, 24, 25, 26	Machine maintenance prioritisation Performance improvement interventions
	Production contingency planning system	Structured methodology for scenario-based planning to address potential production disruptions. Utilises risk assessment and simulation modelling to develop response strategies and evaluate operational impacts.	27	Recovery plan authorizations Disruption threshold definitions
Financial review	Integrated cost modelling and forecasting	System combining activity-based setup cost modelling with subcontracting cost driver analysis. Integrates internal production costs and external sourcing costs into the S&OP process to support production planning and budget decisions.	28, 29, 50, 51	Subcontracting cost approvals Budget reallocation authorizations
Integrated reconciliation	Workforce capability and availability system	Structured framework for defining, categorising, and managing employee skills and competencies. Includes learning curve models to predict skill development rates and proactive analysis of gaps between current capabilities and future requirements.	30, 31, 32, 33	Critical skill development focus Learning curve accommodation planning

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Table A5. Continued.

S&OP process step	First-order IPC-building strategies	Description	Second-order IPC-building strategies	Supported S&OP decisions
Task and resource management system		System for decomposing tasks into required skills and competencies, optimising resource assignments, and tracking availability across departments. Includes performance analysis, productivity forecasting, and structured substitution mechanisms.	34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44	Workload balancing adjustments Resource substitution authorizations
Custom material and subcontractor management		System for predicting demand for custom materials and tracking their status through the supply chain. Includes structured repositories of supplier and subcontractor capabilities and tactical make-or-buy assessment frameworks.	45, 46, 47, 48, 49	Supplier qualification requirements Tactical make-or-buy determinations
Executive S&OP meeting	Strategic sourcing and competency alignment	Framework for aligning long-term sourcing strategy with organisational capability development. Evaluates trade-offs between strategic value (building core competencies) and operational expediency (short-term cost savings, immediate capacity needs).	52	Resource allocation confirmations Cross-project prioritisation Core competency strategic decisions Long-term sourcing partnerships Strategic make-or-buy policy directions Organisational capability development priorities