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Title: "Reconciling engineer-to-order uncertainty by supporting front-end decision-making"

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This paper presents the dynamics of engineer-to-order (ETO) practice through Integration Definition for Function Modelling (IDEF) practice. The paper describes and defines how an ETO manufacturer utilised IDEF-QA in order to manage project uncertainties within the tendering process. The research is conceptualised through an empirical action research approach, involving an active role in the assessment of the ETO process. The paper revisits the use of IDEF, showcasing an assessment of output quality. It also suggests a road map for resource uncertainty within ETO, specifically when scoping the supply chain for ETO projects. The paper then presents an IDEF Quality Assessment model for improving the tendering process of ETO, and it examines the importance of evaluating project behaviour for supporting new future projects. The principal contribution is in how a structured approach provides IDEF with a quality assessment of resources, thereby consolidating and establishing a relationship for highlighting the uncertainties experienced by ETO manufacturers within the decision-making process.

Key Words: Engineer-to-order; tendering; IDEF; process quality, decision-making

Nomenclature:

A	"Average" Ranking of 0.8
AA	"Above Average" Ranking of 0.9
AR	Action Research
BA	"Below" Average) Ranking of 0.7
$C_{1,2,3,..n}$	Represents control number
C_{iITj}	Represents impact of control i on the tool j
$C_{io,}$	Represents quality of control i
CSR	Certificate Signing Request
DFD	Data Flow Diagrams
ETO	Engineer-to-order (ETO)
GRAI	Graphs with Results and Actions Inter-related
H	"High" Ranking of 0.95 and
HC	"Highly-Critical" Ranking of 1
I_{iITj}	Represents impact of input i on tool j
$I_{1,2,..r}$	Represents inputs number from 1 to r
$I_{iQ,}$	Represents quality of input i
ICAM	Integrated Computer Aided Manufacturing
ICOMS	Inputs, controls, outputs and methods
IDEF	Integration Definition for Function Modelling
IDEF-QA	Quality Assessment (IDEF-QA)
IDEF A1	Tender Preparation
IDEF A1.1	Tendering Review
IDEF A1.2	Pump selection
IDEF A1.3	Submission of Bid
IDEF A12	Pump Design
L	"Low" Ranking of 0.6,
O_{mQ}	Represents the output quality and m denotes output 1,2, 3 …m
O_{TIkm}	Represents the impact of tool k on m output
SADM	Structured Systems Analysis & Design Method
$T_{1, 2,3,k}$	Represents tools (including resources within the IDEF 1 to k)
$TF_{1..k}$	Represents the transformation function for tools 1 to k
T_{Qj}	Represents quality of tool j

1 Introduction

Through the growing popularity of customer-driven manufacturing, firms have undergone many changes in terms of their product offerings in order to meet increasing variability in demand. Many organisations have been forced to revisit their internal capabilities in order to respond to economic turbulence and uncertain demand profiles (Ismail et al, 2007). Whereas the variability and the uncertainty characterising project-based, engineer-to-order (ETO) companies generates significant complexity as ETO coordinates its design, engineering-to-production delivery requires specifically tailored managerial solutions to handle all the processes (Raham et al, 2003; Browning, 2014: Pinto et al, 2017). For instance, Gosling and Naim (2009) highlighted that ETO is driven through the actual customer orders and state that 'one-size-does-not-fit-all'. Gosling and Naim, (2009) concluded that different information items are generated, accessed and exchanged between organisations and they must continually 'flow' through them. Cameron and Braiden, (2004) suggested that a mapped process is one method of understanding how processes are integrated, managed, coordinated and controlled. However, this flow of information for decision-makers often relies on information and resources, and the interconnections of these relationships, such as internal (functional departments such as sales and engineering) and the external stakeholders (suppliers, customers and regulators from industry) being more accurate and up-to-date. There is, however, a variation to the quality of information that is being captured. For example, the process of ETO is usually executed through a number of linear activities within the business process: tendering; design; procurement; manufacture; installation and commissioning (Konijnendijk, 1994, Hicks et al, 2009).

Furthermore, Ergen et al (2007) highlighted that the information related to the management of an ETO process is challenging due to the complexity of the information flow between all parties involved in the project. The aim of this paper is to improve the tendering process within ETO by potentially improving the process quality, through a more robust sequence of activities. Taking a broad view of supply-chain uncertainty the intention is to improve the ETO supplier relationship through a more structured approach, between customer and supplier, within the context of ETO, to identify root cause. In summary, this paper investigates how an extended business process model can provide a deeper contribution, improving the scoping of an ETO project. This paper contributes to the literature through investigating the front-end in the ETO sector, from a resource perspective, focusing on the case example of tendering. The aim of the paper is also to provide an extension to the Integration Definition for Function Modelling (IDEF) methodology, thereby allowing front-line decision-makers to evaluate the quality of resources involved in a complex process, such as tendering where the information is critical to the scoping of a project (Konijnendijk, 1994; Willner et al, 2016). In summary, the objectives of this paper are: to provide examples of the adoption of an extended IDEF modelling approach, to the processes within ETO; to point out a new direction for assessing the uncertainty of the processes in terms of capturing identifying the root cause; to suggest future research themes in ETO, in terms of uncertainty and complexity.

2 Literature Review

Within the ETO literature, ETO firms comprise approximately one-fourth of all North American manufacturers (Grabenstetter, and Usher, 2014). These manufacturers are often defined as producing one-off projects, frequently unique, and are primarily associated with large, complex project environments in sectors such as construction and capital goods (Hicks et al, 2000; Cameron and Braiden, 2004; Tsou, 2008; Naim, and Towill 2013a; Browning, 2014; Gosling et al 2015, Mello, et al, 2017). ETO manufacturers often encounter higher levels of uncertainty compared to other manufacturing typologies (Muntslag, 1994). A typical ETO manufacturer supplies unique products that have similar features, and the manufacturing operation is based on receiving a customer order and developing a technical specification accordingly, within the scope of work (Silventoinen et al, 2014). In fact, ETO is usually facilitated through a project environment, which means customer orders are often coordinated as projects (Yang, 2013). One of the main challenges for ETO is managing the process of uncertainty. ETO projects are frequently characterised as one-of-a-kind, with the high levels of customisation and are therefore complex in nature. As a consequence of the one–off nature of ETO, manufactures tend to operate a ‘turn-key’ operation through an extensive supply chain with the decoupling point located at the design stage (Wikner, and Rudberg, 2005; Gosling et al, 2013a).

One of the main challenges for maintaining customer value across the ETO process is the ability of operations to respond to obstacles associated with uncertainty (Childerhouse and Towill, 2004). Muntslag (1994) identified three uncertainty factors: product mix of volume; product uncertainty; and process specification uncertainty. A study by Hendry (2010) of 24 UK manufacturing ETOs suggests that certain core capabilities are needed, including the investigation of the strategic overview, in order to secure repeat business and the importance of the supply chain. Supplier involvement coupled with engineering and production related activities results in a non-linear approach to supply chain management. Finally, Wang et al (2010) justified a more structured approach for capturing those uncertainties within an intricate supply chain, such as ETO. Despite these high levels of ETO, Hicks et al (2001) identified that they could learn from similar uncertainties associated with the lessons from the high volume sector, such as focusing on the reduction of the supplier base and long terms relationships. However, the characteristics of ETO markets significantly constrain the application of the more established supply chain management methods, as ETOs are exposed to higher levels of risk, and knowledge is often vague and uncertain (Hicks et al, 2001; Hendry et al, 2004; Batson and McGough, 2007; Grabenstetter, and Usher, 2014). Hence, focusing on more visual management of the firm, and the quality of the relationships within a complex knowledge exchange (see Wu et al, 2013, Haug, 2013), can help ETO companies to obtain quantifiable information in terms reliability of the internal and external processes. In the presence of uncertainty, the confidence levels maybe be 'fuzzy' due to the uncertainty in identifying the cause; the extent of the uncertainty and its potential impact (Bing, 1999; Rashid and Ismail, 2007, Reid and Smyth-Renshaw, 2012).

2.1 Root Causes in the ETO Tendering Process

The tendering processes with ETO is often fragmented, involving the coordination of many tasks and individuals, to make decisions regards whether to participate in the tender or not (Mohemad et al, 2010). The tendering process usually starts when an ETO manufacturer commences an invitation to bid from a contractor. The purpose is to invite a suitable sub-contractor to present a package of work and established price for the work (Hackett et al, 2016). When a contractor makes an enquiry, they will usually scope out other ETOs manufacturers at the same time, allowing them to compare each tender before placing their order. The process often involves significant discussions to define the scope of work, which includes: the client specification; engineering design; scope of supply and quality plan. The tender will also present a program within the parameters of: delivery; technical performance; quality & compliance; price commercial; and contractual conditions within the contract, as presented in figure 1.

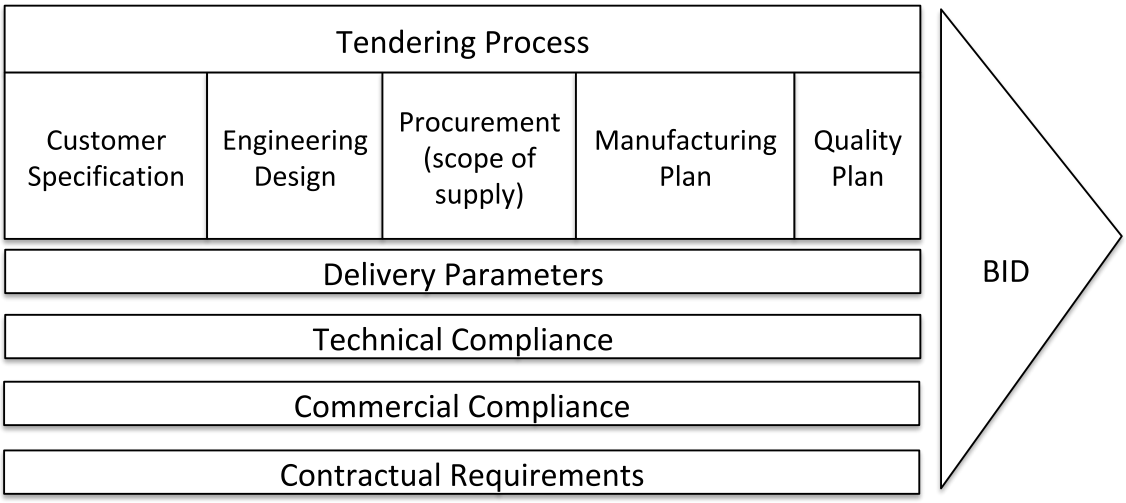

Figure 1 ETO Tendering Process (adapted from Laryea, 2013)

This structure forms the criteria for the bid that will be evaluated by the main contractor (Laryea, 2013). The process regularly consists of numerous iterations, developing a series of alternative solutions for a single project, driven by the parameters of cost and delivery, of which only one will be built. Uncertainties relating to: submission; documents; participants and the working hours thus affecting the output; and ultimately the associated costs can hamper the efficiency of the tendering. Conventionally, these decisions are often based on a blend of their intuition, their subjective judgement, which is based on past experience and does not guarantee consistent decisions or identifying the root cause.

There is also the notion that the supply chain may impact on innovation and performance of the project in its entirety (Gosling and Naim, 2009; Böhme et al, 2014). In turn, the operation of ETO often relies on the organisation’s ability to respond to obstacles associated with higher levels of uncertainty within the operation (Childerhouse and Towill, 2004; Gosling et al, 2013) and supply chain innovation (Böhme et al, 2014). In order to create greater transparency, as well as the perspective of protecting crucial knowledge to the ETO process, we propose that the information captured in a business process may be organised and conveyed through various views (Browning and Ramasesh, 2007; Browning, 2010; Adrodegari et al, 2015). The added ability to track down the root cause within a process is key for any manufacturer and is critical in the event of a component failure or process non-conformance (Reid and Smyth-Renshaw, 2012). Hicks et al (2001) highlighted that many ETO organisations have developed efficient business processes, which they have deployed across functions. Considering well-established methodologies for systems modelling (e.g.: IDEF for structure; Data Flow Diagrams (DFDs), Structured Systems Analysis & Design Method (SADM) for information flow; Graphs with Results and Actions Inter-related (GRAI) method for decision centre hierarchies and material flow (Vosniakoss and Barla, 2006)) provide a means of capturing the 'as-is' approach. Similar research highlights that a mapped process is one method of understanding how a process is integrated, managed, coordinated and controlled, or is vulnerable and inefficient (Cameron and Braiden, 2004; Verdouw, 2011).

2.2 Understanding the value of process models

ETO manufacturers often encounter higher levels of uncertainty compared to other manufacturing typologies (Muntslag, 1994). A typical ETO scenario is often based on numerous assumptions or on incomplete, inaccurate, unavailable or partially missing information and data within the design making process. This often erodes the reliability of the decision-making process. Through the adoption of a structured modelling approach, supported by an assessment mechanism regards supply chain quality, the variances of key quality characteristics within the process can be identified (Tsou, 2008; Verdouw et al, 2011).

2.3 The adoption of IDEF

An established modelling technique, Integration Definition for Function Modelling (IDEF), is a compound acronym (Icam DEFinition for Function Modelling), where 'ICAM' is an acronym for Integrated Computer Aided Manufacturing, a well-tested language, and comprehensive systems modelling technique (Chin et al, 2006; Waissi et al, 2015). The IDEF modelling technique is designed and developed to facilitate understanding, as an instrument for business process reengineering (Soung-Hie 2002). It is considered one of the strongest modelling approaches for the support of complex systems (Yigit and Allahverdi, 2010) and is therefore suitable for representing process flow descriptions of the complex and intricate processes in an ETO supply chain. IDEF adopts a probing approach for capturing the process characteristics in a qualitative format and provides the platform for identifying the resources, in terms of inputs, controls, outputs and methods (ICOMs) through a connecting network that ties the processes together (Ismail et al, 2007). It presents a clear description about input information, output information, and resources of a process concerned in a hierarchical and systematic way. Furthermore, IDEF employs a top-down method that starts from general activities and moves into more specific process issues, providing a means to capture the 'as-is' model shown in Figure 2.

IDEF combines graphics and text to gain a greater understanding of how activities operate and how they interrelate with each other (Gingele, et al, 2003). According to Waissi et al (2015) IDEF models are well defined, well-structured, easy to understand, straightforward to modify and use, and can be extended to any depth of detail. Thus, they can help to represent, as well as streamline, the overall process.

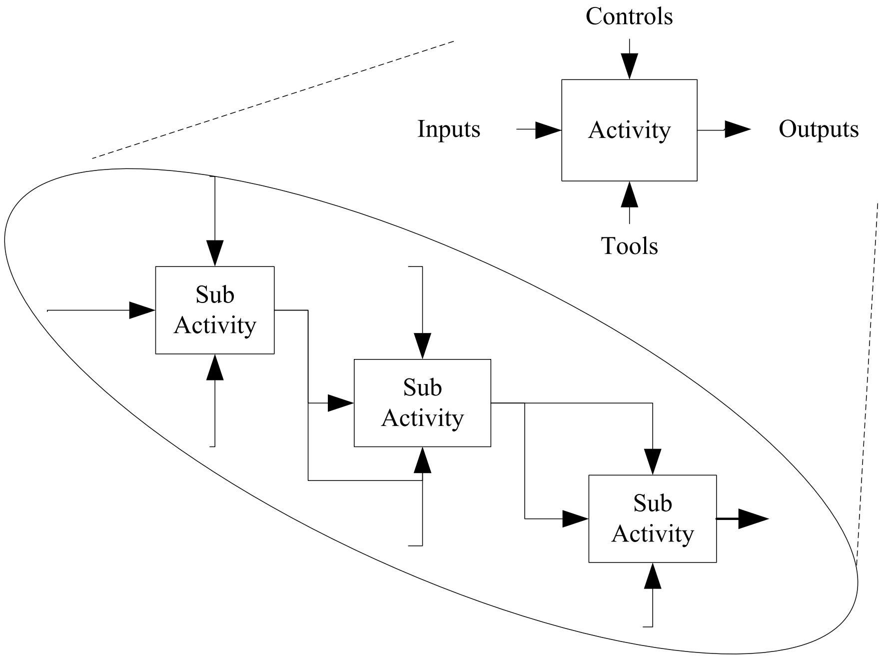

Figure 2 IDEF Task Structure

However, despite the almost universal acceptance of the usefulness of the IDEF methodology, a number of constraints have been highlighted in the literature (Busby and Williams, 1993; Zhang et al, 1999; Soung-Hie et al, 2002): i) it is a static representation of the system; ii) it has a limit of functional precedence; iii) it is not a quantitative model, and is therefore difficult to use as a compelling process reengineering approach; iv) it is inadequate for analysis and design of the supply chain. The main drawback with IDEF is no quantitative assessment in place, in terms of assessing the quality of the process, i.e. the evaluation of the quality of the ICOMS. Furthermore, Koh and Gunasekara (2006) stated that managing uncertainty is a knowledge-intensive activity and the role of the project manager is a key enabler. Rashid and Ismail (2007) identified that firms continually challenge, review and revise or renew their routines in response to change through process models in order to reengineer their business processes to simulate and verify the dynamic behaviour ETO.

3 Proposition: Extended IDEF Approach

3.1 The IDEF Quality Assessment (IDEF-QA) model

Through the adaptation of an established approach like IDEF, the proposed IDEF Quality Assessment (IDEF-QA) is designed to highlight a level of uncertainty through the adoption of a quantifiable assessment of the resources (or ICOMS) of the IDEF model. The extended IDEF model aims to identify the level, or extent of the uncertainty, through the IDEF 'quality' assessment in order for practices to react accordingly – it uses extended syntax and semantics to identify the links to the ISO 9001 quality standard and visually highlights them for redesign (Gingele et al, 2003; Sing et al, 2011).

3.2 IDEF Qualitative and quantitative criteria

A five level qualitative scale is used to represent the quality of the inputs, controls and tools. These are "low" (L), "below average" (BA), "average" (A), "above average" (AA) and "high" (H). A similar scale is used to describe the relationships in the assessment matrices with an additional level of "highly critical" (HC). For example, the highly critical "HC" score would indicate that the impact of an input on the tool is highly significant and that the input must be available for the tool to function. To obtain quantitative measures for the activity outputs, the qualitative assessments described above are transformed into quantitative values (1=HC and 0.6=L) selecting from a number of scales dependent on the type of input, tool or control and the type of application the approach is used for (see, Table 1: Assessment Weightings). Two scales could be used; the first is a linear scale, for example, to represent physical types of resources. The second is an offset linear scale, for example, to represent a minimum threshold of requirements before an input is considered available or low (L).

Table 1. IDEF Quality Assessment Weightings and Coding Label

Qualitative scale	**Quantitative Scale**
“Highly Critical” (HC)	1
“High” (H)	0.95
“Above average” (AA)	0.9
“Average” (A)	0.8
“Below average” (BA)	0.7
“Low” (L)	0.6

As described above, the scale used follows where “Low” (L) is 0.6, “Below” average (BA) is 0.7, “Average” (A) is 0.8, “Above Average” (AA) is 0.9, “High” (H) is 0.95 and “Highly-critical” (HC) is represented by the number 1, deemed critical to the activity. An example of the extend IDEF model depicting the quality assessment is presented in Figure 3, with the intention to provide an IDEF integrated support tool to enable individuals to identify the output quality of resources being adopted within a particular project. In this case the quality of the underpinning procedures within the application of the process of tendering within ETO. The next section elaborates on this idea in more detail.

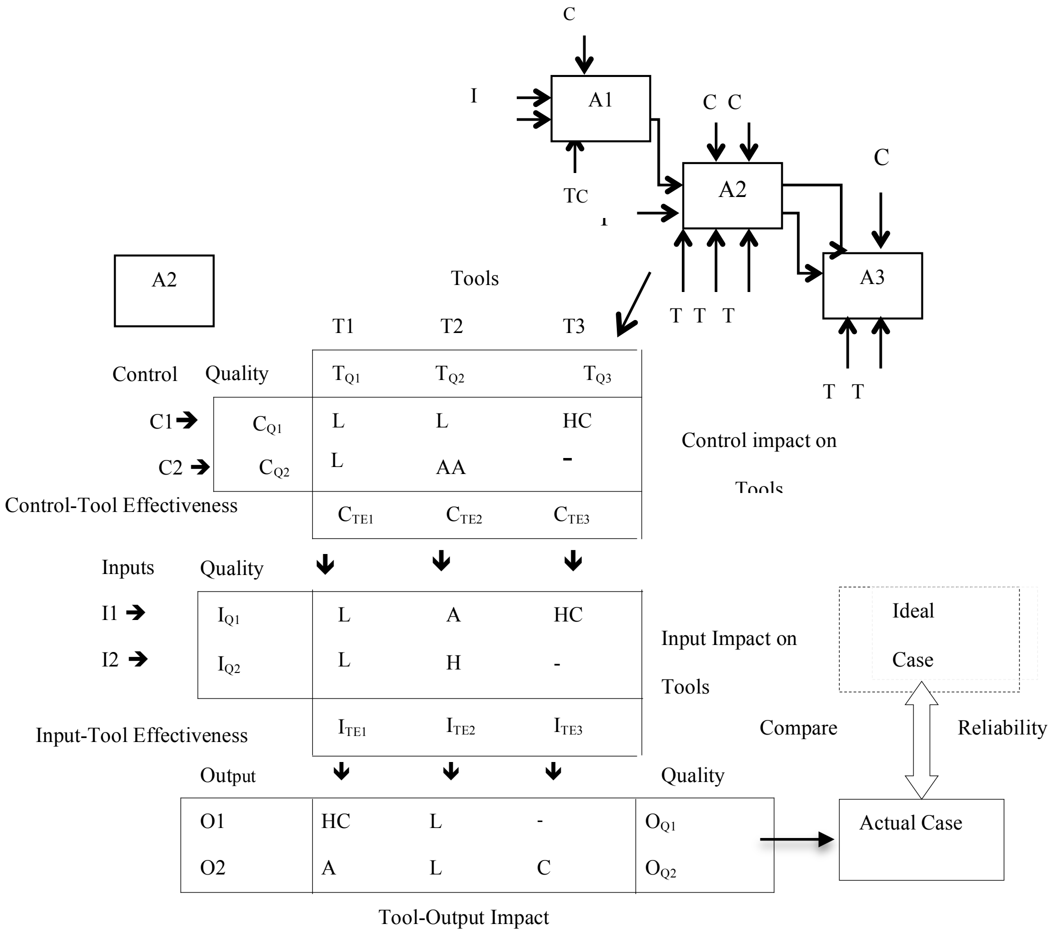

Figure 3 IDEF Quality Assessment (IDEF-QA)
(Adapted from Rashid & Ismail, 2007)

3.3 The Quality Assessment

The proposed extended IDEF approach, referred to as IDEF-QA, is designed to be a management support tool with the overarching objective to provide a quantifiable method of establishing the perception of quality of the ICOMS within the process of ETO, to ascertain the output quality within a key ETO process such as tendering (Willner et al, 2016). With the introduction of the additional quantitative element, ETO identities the qualities associated with the process ICOMS. It can enable managers through a more informed view in terms of their decision-making processes, to identify the uncertainties and possible root causes within a particular problem, it can therefore influence the outcome of the ETO process.

In order to represent the multidimensional characteristics of the IDEF-QA, the model consists of three assessment matrices. These are designed to complement the IDEF ICOM methodology through control-tool impact, input-tool impact, and output quality. The adopted approach is based on sequentially assessing the quality of each IDEF activity box, which is the combined quality of resources within the ICOM classification, defining a particular activity. The next section presents the assessment methodology with supporting calculations.

3.3.1 Quality Assessment: Control

Barney (1991; 2001) clearly defines an organisations resource, in terms of assets (plant, equipment, land, raw materials, inventory), capabilities (organisational processes, information and knowledge), and human capital (training, intelligence, and experience) within an organisation. The first is a "control-tool impact" matrix representing the impact of each control on individual resources or tools and, when combined with the control quality, produces a normalised "control-tool effectiveness" measure for each resource or tool involved in the ICOM structure of IDEF. In terms of the representation in the extended IDEF, these resources and tools have been categorised under the title of tools as they support the facilitation of the activity within the IDEF model. Where:

- $T_{1,\,2,3,k}$ represents tools (including resources within the IDEF 1 to k
- T_{Qj} represents quality of tool j
- $C_{1,2,3,..n}$ represents control number
- $C_{iQ,}$ represents quality of control i
- C_{iITj} represents impact of control i on the tool j

The Control Tool Effectiveness for tool *j* is (C_{TEj}) and is calculated and normalised as follows:

$$C_{TEj} = \sum_{i=1}^{i=n} \left(C_{iQ} \cdot C_{iITj} \right) \Big/ \sum_{i=1}^{i=n} C_{iITj} \qquad (1)$$

3.1.2 Quality Assessment: Tool

The second is an "input-tool impact" matrix, which represents the input requirements and impact for each tool. Combined with the input quality or availability, the second matrix produces a normalised "input-tool effectiveness" for each tool. Where:

- $T_{1,\ 2,3,k}$ represent tools 1 to *k*.
- $I_{1,2,..r}$ represents inputs number from 1 to *r*
- $I_{iQ,}$ represents quality of input *i*
- I_{iITj} represents impact of input *i* on tool *j*

The Input Tool Effectiveness for tool *j* is (I_{TEj}) and is calculated and normalised as follows:

$$I_{TEj} = \sum_{i=1}^{i=r} \left(I_{iQ} \cdot I_{iITj} \right) \Big/ \sum_{i=1}^{i=r} I_{iITj} \qquad (2)$$

3.1.3 Quality Assessment: Output

The third matrix is a tool-output impact matrix that identifies to what extent each tool contributes to each output. When this matrix is combined with the tool quality, control-tool effectiveness and input-tool effectiveness, the result is a normalised measure of the output quality. Where:

- O_{mQ} represents the output quality and m denotes output 1,2, 3, ….*m*
- $TF_{1..k}$ represents the transformation function for tools 1 to *k*

- O_{TIkm} represents the impact of tool *k* on m output

The output quality for output *m* is, therefore, calculated and normalised as follows:

$$O_{mQ} = \sum_{j=1}^{j=k} \left(TFj \, . \, O_{TIim} \right) \Big/ \sum_{j=1}^{j=k} O_{TIim} \tag{3}$$

Where ;

$$TF_j = \sum_{\mathrm{i}=1}^{\mathrm{i}=r} \left(I_{\mathrm{iQ}} \, . \, I_{\mathrm{iITj}} \right) \Big/ \sum_{i=1}^{i=r} I_{iITj} \sqrt{\mathrm{T}_{\mathrm{Qj}} . \left(\sum_{i=1}^{i=n} \left(C_{iQ} \, . \, C_{iITj} \right) \Big/ \sum_{i=1}^{i=n} C_{iITj} \right)} \tag{4}$$

4 Methodology

A case study was adopted in order to explore and validate the concepts proposed, as well as to assess the level of uncertainty in the case of ETO. The Action Research (AR) (Zimina et al, 2012) element is linked to the development and experiment of IDEF within the manufacturing environment of ETO. The authors took on the role of observer and analyst within the organisation, which included a participative role within the models development and experimentations (c.f. Aquilani et al, 2017). The objective here was to develop and embed the extended IDEF approach, designed to address the uncertainties within the process and to assess the quality of resources by highlighting some of the process vulnerabilities. Baskerville and Wood-Harper (1996) suggest that, by merging research and praxis, AR generates a large amount of data and produces relevant findings which supported the construction of the IDEF maps prior to the assessment. Furthermore, Baskerville and Wood-Harper (1996) highlighted that AR as a method compliments the post-positivist paradigm. These elements fit extremely well with the pragmatic paradigm adopted here. From an epistemological perspective, AR is consistent with operations management thinking, as they both assume that the most efficient way to acquire and develop knowledge is by participant experiment in a live environment (Zimina et al, 2012).

The authors had established long-term collaboration with a specific ETO organisation, formally and contractual, as they were willing and keen to experiment with innovative approaches to improve their product development process. A researcher was therefore directly involved and worked within the ETO project team on a daily basis over a 42 week period. He, acted as the developer and assessor of the IDEF maps, as well as supporting the decision-makers to question uncertainties by initiating review sessions, or IDEF Quality Assessments, in order to verify the nature of output. These observations formed part of the AR data collection techniques and, over three years the researcher kept an extensive diary, developing the richness of observations that could not have been gathered otherwise. The IDEF project resources provided the firm with an improved competitive advantage (Grant, 1991; Yoo, Lemak & Choi, 2006) in particular in the supply chain (Chae et al, 214; Nakano et al, 2013). Therefore, IDEF was considered an appropriate technique to represent the process prior to investigating the uncertainties in an ETO application.

For this investigation the following research questions (RQs) were developed: RQ1: Is an extended IDEF model capable of highlighting uncertainty within the Tendering process?; RQ2: How can an extended IDEF minimise the levels of customer uncertainty at the scoping stage of an ETO project.

4.1. Case study method

The assessment of a number of ETO projects was examined by adopting a case study research methodology to explore and address the research questions. This design fits well within the case study research category as it is recognised as being particularly valuable for examining a phenomenon and providing some clarifications (Yin, 2013).

Voss et al (2002) also recommended this approach for theory development as well as theory testing. Considering the dimensions of the proposed model, the case study approach is deemed appropriate (Yin, 2013).

4.1.1 Data collection

The data collection included the analysis of an ETO organisation over a period of 24 months covering a variety of projects to gain an understanding of the business, with a lead-time of 35 to 42 weeks. In conjunction with this, a series of IDEF training workshops were undertaken prior to the anticipated IDEF-QA assessment, including the assessment of the IDEF-QA the company's perception of the extended IDEF ideology via observations and interviews. The focus of the study and the results presented below sought to validate the proposed conceptual IDEF-QA.

4.1.2 Data analysis

The IDEF mapping activity was coordinated through multiple review meetings during which the researcher facilitated assessment, as well as communicated the results. The researcher adopted the AR approach in terms of following: (a) what to measure; (b) when and where to analyse; (c) how to analyse (which includes the modelling adopted within the company). At the end of the data collection stage, the entire ETO process (Sales, Tendering, Project Management, Design, Procurement, Manufacturing, Assembly, Testing, Installation and Commissioning) was mapped using the traditional IDEF approach. This comprised 32 IDEF process maps, including over 90 iterations in order to capture the ETO blueprint of the business, as well as validating the IDEF model. The researcher also explained the numerous uncertainty levels of the ETO and this information created key measures for reviewing the project performance, as well as identifying potential weaknesses within the ETO process, in terms of the resource quality currently adopted.

5 Findings - An example of the IDEF–QA within an ETO Project

5.1 Case Study Company

The IDEF-QA proposal was coordinated within an ETO manufacturing company that designs and manufactures hydraulic pumps. The case study company had an annual turnover of over £162.5M and employed 500 people at its UK manufacturing site. The product portfolio was grouped into two main categories: standard pumps and non-standard pumps with an allocation of direct labour hours as presented in Figure 4. The number of project hours allocated to each product type varied from 904 to 3466 direct hours across the core project steps: order entry; engineering; machining/welding; assembly testing/bare pump; packaging; testing/systems; other (contracts). The company's standard pumps used common components and were either manufactured to order, or directly made-to-stock. However, with their non-standard pump range, they encountered numerous modifications based on customer-specific specified functional and performance requirements, which often pushed the boundaries of technical performance. As a result of these exceptional requirements their products encountered higher levels of uncertainty, project complexity, supplier disruptions, and financial risk.

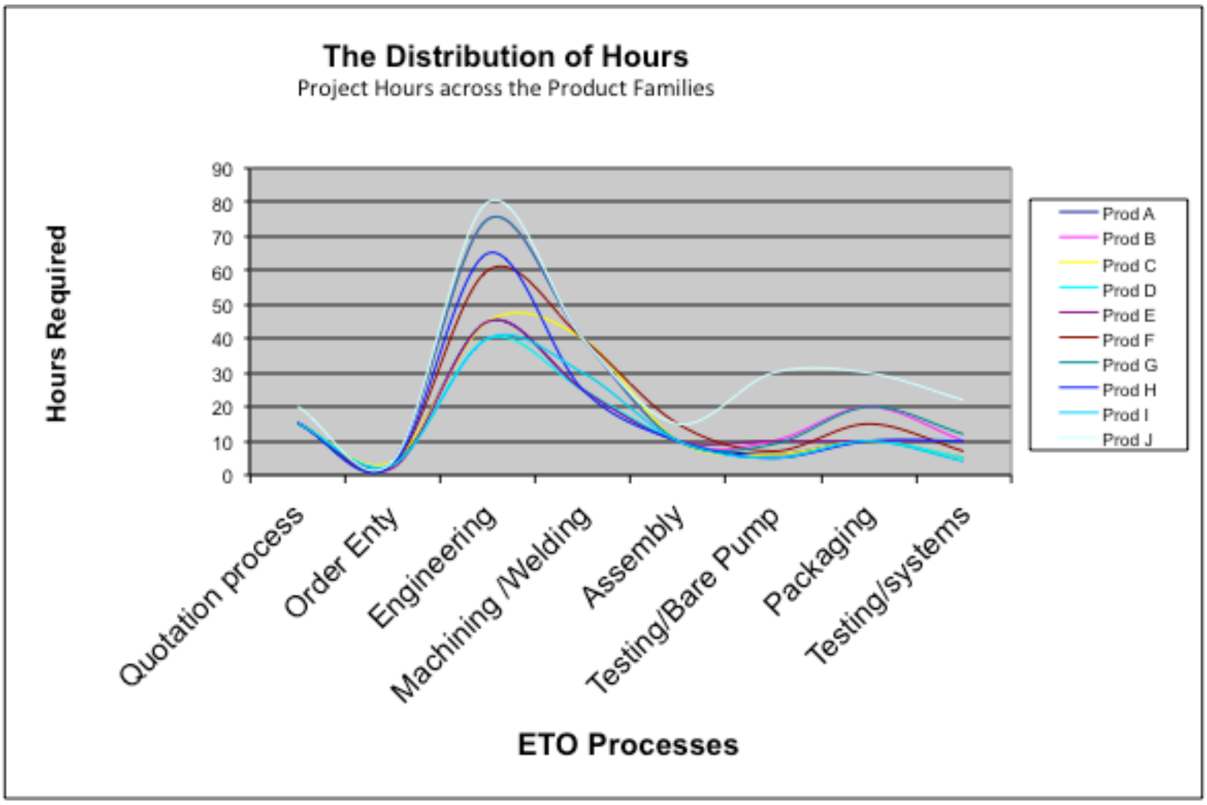

Figure 4 Distribution of hours across the product types

Despite the company being accredited to the ISO9000 quality management system, it was often exposed to repeated mistakes within their pre-manufacturing (Sales, Tendering, Project Management, Design, and Procurement) processes whilst the pump ‘scope of work’ is being developed. For example, each ETO order is managed directly by a project manager, who coordinates the scope of work, including the commercial and technical aspects, as well as managing the external relationships, namely the customer and the supply chain.

5.1.1 Transparency of the process

During the review of the firm’s business processes the researcher highlighted a lack of process transparency. For instance, project managers were exposed to similar repeated issues relating to supplier problems delays, overruns, and other quality related non-conformances. For example, Ben-Ammar, Dolgui, and Wu (2018) suggested that decision makers of real applications (with complex structures) neglect seeking optimal solutions, often relying on approximate alternatives when good quality decisions are satisfactory. Subsequently, the researcher sought to capture the extent of these uncertainties within the context of supplier selection through the adoption of the IDEF process models and ultimately the IDEF-QA. Hence, the importance of capturing the ETO process was as a method of comparing process similarities, as well as identifying the root cause associated with uncertainty. The conceptual IDEF-QA was deemed necessary in terms of developing a 'proof of principle' within the context of ETO. The assessment was facilitated by 12 core members from the organisation's management team, as they possessed of the necessary experience of producing one-off ETO projects.

The company also provided supporting documents relating to product development, quality management procedures, quality reports and project files which were used as a reference for understanding the product development and project management processes. The findings of the IDEF model were disseminated to all stakeholders within the organisation in terms of understanding the current business issues as well as capturing the knowledge, levels in order to support the future decision-making in ETO.

Through the notion of visibility management, the IDEF methodology demonstrated the quality of the company's resources (quality documentation, project reports, management information, meeting minutes, individual interviews and ICT systems), from staff directly involved in the ETO project. A total of 23 managers, engineers and specialists were involved in IDEF-QA activity. The analysis of four ETO projects within the company identified the broader issues in the relationships across multiple projects in order to draw some comparisons. As a result, the development focused on the identification of critical resources within the IDEF in terms of the resource base. The subsequent model was selected to demonstrate the applicability of the proposed IDEF-QA and drew from the literature review, the initial observation of the four ETO projects, and the IDEF reviews with the managers. The following presents the IDEF reference model to share the key steps of the assessment, as well as to define the quality and associated risk within the constructs of the ICOMs, such as: control-tool impact; input-tool impact; and output quality.

5.2 Quantitative assessment and output quality

This section describes the “control-tool effectiveness”; “input-tool effectiveness”; “transformation function” and “output quality” of the IDEF diagram. The transition of the qualitative assessment to quantitative assessment was carried out via the assignment of qualitative assessments of inputs, outputs and impact factors, as described in section 4 and 2. Figure 3, the results of the IDEF QA for the “Tender Preparation”, is supported by a summary table. Through the adoption of a five level qualitative scale identified in section 3.2, Table 4 in section 5.2.1 presents the translated quantitative assessment derived by sequentially applying the equations presented in section 3, the IDEF Quality Assessment (IDEF-QA) proposition.

5.2. Tender Preparation Process

The tendering preparation process was identified as the initial “point of commitment” within the ETO supplier selection. Here, the potential suppliers are identified within the customer’s specification or selected through the company’s approved supplier list. The activity involves the documentation of incoming pump orders from the customer; identification of standard or non-standard pumps; and selection and submission of bids. It provides a link between customers and design engineering as it acknowledges the receipt of enquiry and received orders, and confirms all technical and commercial aspects of the order. The tender also included the pump type and changes, if required, to a customer's specification, based upon decisions taken by the design team if the customer's specifications could not be strictly met. The "Tender Preparation" activity is broken-down into three sub-activities within the IDEF model in order to determine the necessary inputs, controls, and tools to produce a specific output as illustrated in Figure 5. The sub activities are "tendering review" (A1.1), "pump selection" (A1.2), and "submission of BID" (A1.3).

5.2.1 Results Assessment: A1- Tender preparation

The tender activity is a critical process as it establishes the criteria for identifying the various signals of supplier reputation: brand credibility; supplier references; subcontractors' Certificate Signing Request (CSR) procedures; price, as well as the past experiences working with the subcontractor (Biong, 2102). In terms of the IDEF-QA, the output quality for the "tender preparation" activities is given in Table 2 and Table 3 respectively. The results for the initial review of the competency of resources involved in the customer requirements showed that the output quality of the first activity was 0.90, a "High" score and then declines through each subsequent stage to reach 0.59 as a result of the marginal drops as the output quality is eroded through certain tools underperforming within the process, for example the submission of documents being described as poor quality, only scoring 0.6 in table 3.

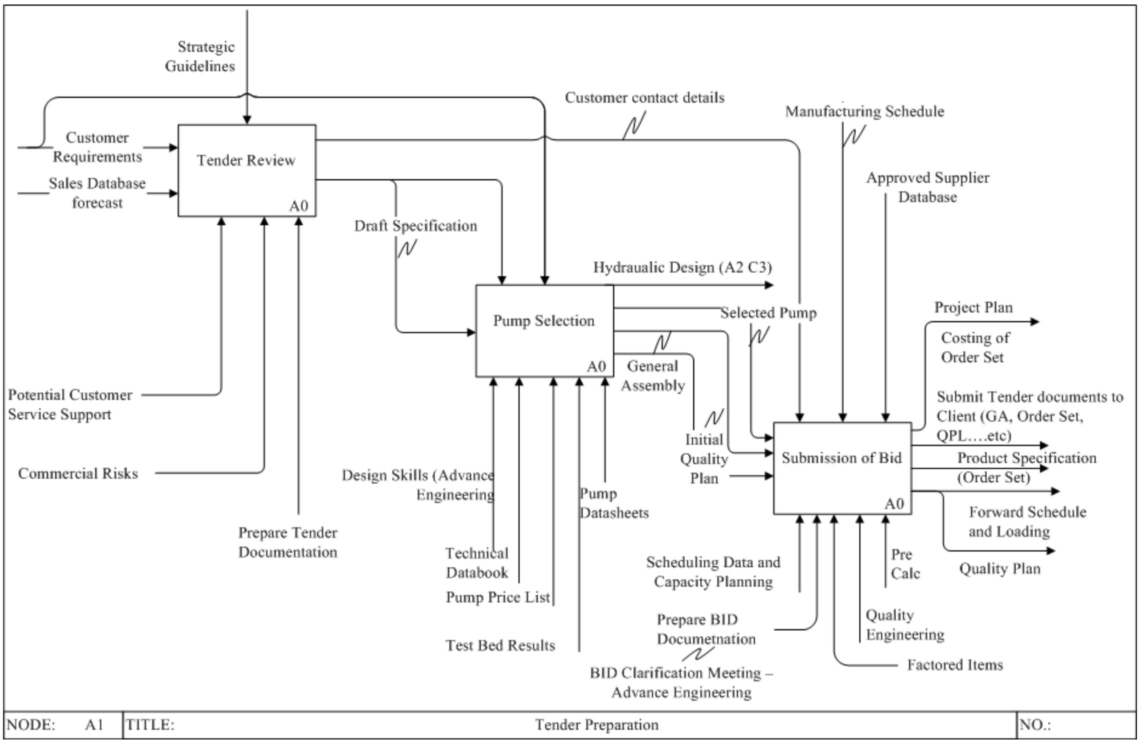

Figure 5 A1- Tender Preparation IDEF model

This transition is to be expected, as the combined effect of unreliable activities is usually far worse than the reliability of any of the constituent sub-activities. Such as different stakeholders types to incorporate elements of design responsibility, social responsibility and contractual agreements within the scope of work. These support the problem of supplier selection and order allocation, often adopting multi criteria decision-making approach on multiple orders (Azadnia et al, 2015).

Table 2 “Qualitative” IDEF–QA of Tender Preparation IDEF-A1

			Potential customer service support	Commercial risks	Prepare Tendering documentation	Design engineering skills (Advance Engineering)	Technical data book	Pump price list	Test bed results	Pump datasheets	Pre-calculation (Costing)	BID clarification meeting-Advance Engineering	Scheduling data capacity planning	Prepare BID documentation	Quality Engineering	Factored Items
A11 Tendering Review	Control		H	H	H											
	A1.1C1 Strategic guide lines	H	A	H	L											
	Input.															
	A1.1I1 Customer requirements	H	H	C	C											
	A1.1I2 Sales database forecast	A	H	H	A											
	Output															
	A1.1O1 Customer/contract details	AA	L	C	C											
	A1.1O2 Draft specifications	AA	A	L	L											
	Control					1	1	1	1	1						
A12 Pump selection	A1.2C1 Customer/contract details				*AA	C	L	A	BA	BA						
	A1.2C2 Customer requirement				H	A	H	L	L	L						
	Input															
	A1.2I1 Draft Specifications				*AA	C	C	C	C	C						
	Output															
	A1.2O1 Hydraulics Design				AA	C	C	L	H	H						
	A1.2O2 Selected pump				AA	C	C	L	A	L						
	A1.2O3 General Assembly				AA	C	C	L								
	A1.2O4 Initial quality plan				AA				H	H						
	Control										H	H	H	H	H	H
A13 Submission of BID	A1.3C1 Customer contract details									*AA	C	H	BA	H	H	A
	A1.3C2 Approved Supplier Data Base									H	L	C		H		C
	A1.3C3 Manufacturing Schedule									A			C	H		
	Input															
	A1.3I1 Selected pump									*AA	C	H	A	C	C	
	A1.3I2 General Assembly									*AA	C	H	A	C	C	
	A1.3I3 Initial quality plan									*AA					C	H
	Output															
	A1.3O1 Submit tender documents									A	C	H	L	C		
	A1.3O2 Product Specification									AA	BA	H		A	A	
	A1.3O3 Project Plan									A		A	C			H
	A1.3O4 Proposed Quality Plan									A		AA	L	L	C	H
	A1.305 Costing of order set									AA	C	AA				H
	A1.306 Forward load (scheduling)									A			C			H

Table 3 Translated “Quantitative” IDEF–QA of Tender Preparation A1

			Potential customer service support	Commercial risks	Prepare Tendering documentation	Design engineering skills (Advance Engineering)	Technical data book	Pump price list	Test bed results	Pump datasheets	Pre-calculation (Costing)	BID clarification meeting-Advance Engineering	Scheduling data capacity planning	Prepare BID documentation	Quality Engineering	Factored Items
A11 Tendering Review	Control		1	1	1											
	A1.1C1 Strategic guide lines	1	0.8	1	0.6											
	Control-tool effectiveness	>>	1.00	1.00	1.00											
	Input.															
	A1.1I1 Customer requirements	1	1	1	1											
	A1.1I2 Sales database forecast	0.8	1	1	0.8											
	Input-Tool effectiveness	>>	0.90	0.90	0.91											
	Transformation function	>>	0.90	0.90	0.91											
	Output															
	A1.1O1 Customer/contract details	0.90	0.6	1	1											
	A1.1O2 Draft specifications	0.90	0.8	0.6	0.6											
	Control					1	1	1	1	1						
A12 Pump selection	A1.2C1 Customer/contract details				0.90	1	0.6	0.8	0.7	0.7						
	A1.2C2 Customer requirement				1	0.8	1	0.6	0.6	0.6						
	Control-tool effectiveness				>>	0.95	0.96	0.95	0.95	0.95						
	Input															
	A1.2I1 Draft Specifications				0.90	1	1	1	1	1						
	Input-Tool effectiveness				>>	0.90	0.90	0.90	0.90	0.90						
	Transformation function				>>	0.80	0.89	0.88	0.88	0.88						
	Output															
	A1.2O1 Hydraulics Design				0.88	1	1	0.6	1	1						
	A1.2O2 Selected pump				0.88	1	1	0.6	0.8	0.6						
	A1.2.O3 General Assembly				0.88	1	1	0.6								
	A1.2O4 Initial quality plan				0.88				1	1						
	Control										1	1	1	1	1	1
A13 Submission of BID	A1.3C1 Customer contract details									0.90	1	1	0.7	1	1	0.8
	A1.3C2 Approved Supplier Data Base									1	0.6	1		1		1
	A1.3C3 Manufacturing Schedule									0.8			1	1		
	Control-tool effectiveness									>>	0.94	0.95	0.84	0.90	0.90	0.96
	Input															
	A1.3I1 Selected pump									0.88	1	1	0.8	1	1	
	A1.3I2 General Assembly									0.88	1	1	0.8	1	1	
	A1.3I3 Initial quality plan									0.88					1	1
	Input-Tool effectiveness									>>	0.88	0.88	0.88	0.88	0.88	0.88
	Transformation function									>>	0.85	0.86	0.81	0.84	0.84	0.86
	Output															
	A1.3O1 Submit tender documents …									0.84	1	1	0.6	1		
	A1.3O2 Product Specification									0.85	0.7	1		0.8	0.8	
	A1.3O3 Project Plan									0.84			1			1
	A1.3O4 Proposed Quality Plan									0.84		0.9	0.6	0.6	1	1
	A1.3O5 Costing of order set									0.86	1	0.9				1
	A1.30O Forward load (scheduling)									0.84			1			1

The analysis indicates the potential disruptions within the IDEF A1 Tendering Preparation processes: with the initial tendering review, pump selection, and submission of 0.9 to an 0.84, in table 4, in terms of output quality as critical. However, the reliability of the quality plan (0.84) and project plan (0.84) improved the "output quality" of the front-end processes within the submission process of the bid.

Table 4 Derived Output Quality: IDEF A1-Tender Preparation
(Adapted from Rashid and Ismail 2007)

A1 Tender Preparation											
A1.1 Tendering Review		A1.2 Pump selection				A1.3 Submission of Bid					
Customer/contract details	Draft specifications	Hydraulics Design	Selected Pump	General Assembly	Initial quality plan	Submit tender documents	Product Specification	Project Plan	Proposed Quality Plan	Costing of order set	Forward load (scheduling)
0.90	0.90	0.88	0.88	0.88	0.88	0.84	0.85	0.84	0.84	0.86	0.84

As the project evolves, the processes continue to become more robust in terms of their output as decisions and utilisation of resources involved improved the output quality process. However, key ETO processes such as Pump Design A12, (see Figure 6) distorted the output quality. For example, the draft specification distorted the Hydraulic Design Information (IDEF: A12.1), in table 5, with a High Critical of 0.95, in terms of output quality, thus pressurising the design capabilities of the organisation. The results therefore influenced the "output quality" of the project's initial quality plan (A12.3) and scoping of the supply chain, thus challenging the company's internal resources (Rashid and Ismail, 2007) and visibility in terms of the supply chain (Pero and Rossi, 2014).

Table 5 Derived Output Quality IDEF A12 Pump Design
(Adapted from Rashid and Ismail 2007)

IDEF A12: Pump Design						
A12.1 Hydraulic Design		A12.2 Pump Selection		A12.3 Pump Arrangement & Quality Plan		
Hydraulic Design Information	Pump Curves & PID	Hydraulic Design	Pump Selection	Parts List	G.A Drawing	Initial Quality Plan
0.95	0.77	0.77	0.77	0.77	0.77	0.72

The analysis leads to the following deduction, whilst there are clearly both process and system inefficiencies, the greatest problems can be traced back to the following: i) Downstream activities are influenced by upstream decisions; ii) Process hotspots are amplified through the IDEF-QA; iii) Too many functional interfaces with the supply chain relationship are often not fully complied with; and iv) An absence of effective mechanisms to control the hand-over points with the hand-over criteria causes additional loading on the business process and resources. By assessing the quality of the ETO process, the human capital was identified as one key resource that improved through a number of steps and contribution within the process. The data was captured through a number of resources: the contributions made by previous initiatives (i.e. project management reviews); the impact of similar schemes which were running in parallel; and post-mortems of past projects, feedback loops, facilitated through project management reviews.

The main issue with the IDEF-QA in assessing the ETOs resource capabilities is that the assessment is time consuming. However, the IDEF-QA can be used as a benchmark against similar ETO projects in the form of a process template for ETO product types. Furthermore, a supporting rationale was developed to decide whether a further IDEF-QA was necessary develop a greater understanding of a particular issue, such as a credit check on a supplier, which was previously incomplete and therefore an insufficient resource to the decision–making process.

It was unfortunate that the case study organisation limited the development of the IDEF models to only sub-levels of innovative projects, due to time constraints. However, the authors investigated a variety of tools for supporting the representation of the IDEF-QA scores. A further recommendation was to adopt a colour coding system within the IDEF model in order to support the visualisation of the assessment thus signposting users to the potential risk and uncertainty of the IDEF–QA scores. This representation is presented in Figure 6, with the nodes relating to the level of uncertainty and IDEF-QA scores within the actual IDEF model with supporting reference key presented in table 6 . For example, the critical nodes represented in red (draft specification, hydraulic design, pump price list, pump data sheet and technical data book) was identified by engineers as the root cause within the pump design that often disrupted the output quality of information within this key process. As a consequence, representatives of the company declared this as a roadmap for identifying potential vulnerabilities within the tendering process. For example, the high uncertainty levels based on the quality of resources are presented as red nodes (high risk score = red indicators), orange represents a amber warning for potential disruption, whilst lower levels in a green compliance to the anticipated expectation (low risk score = green).

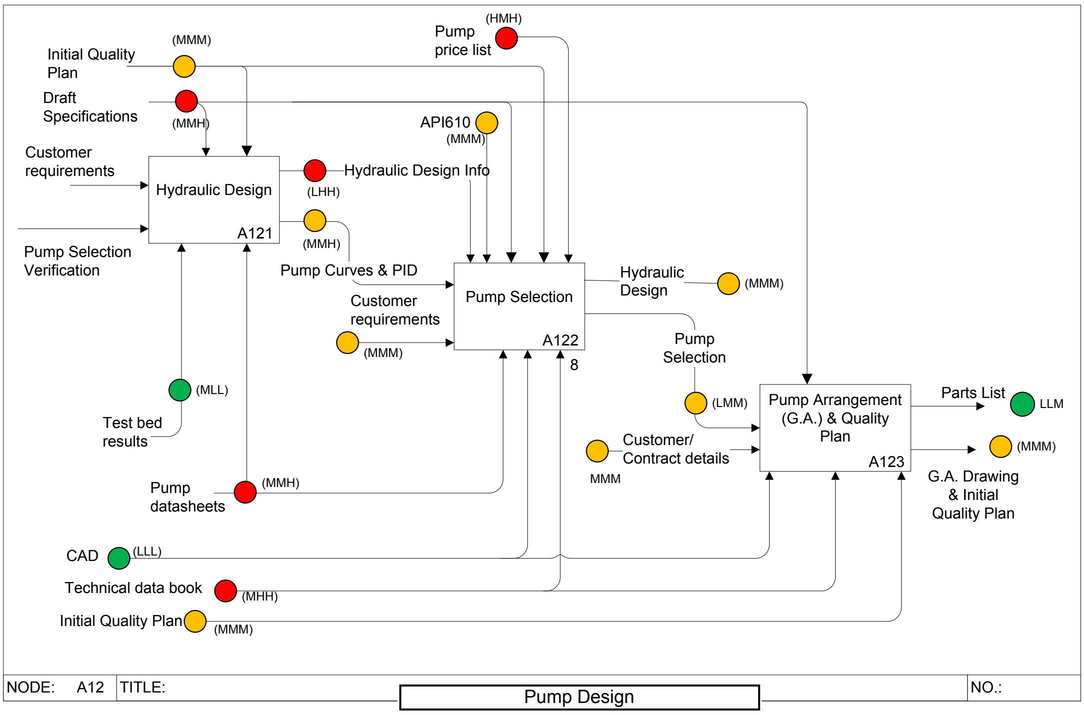

Figure 6 IDEF–QA score within the extended IDEF model

Table 6. IDEF Coding Key

Node Colour	Qualitative Scale	Quantitative Scale
Red	"Highly Critical" (HC)	1
Red	"High" (H)	0.95
Orange	"Above average" (AA)	0.9
Orange	"Average" (A)	0.8
Green	"Below average" (BA)	0.7
Green	"Low" (L)	0.6

6 Discussion

This papers main contribution extends the traditional IDEF approach using the conceptual IDEF-QA assessment in order to reduce the amount of 'project drift' within the ETO process for decision-making within the supplier selection, based on technical and commercial considerations. Through integrating evidence from the literature, case studies, and action research, we have also identified a method of determining the output quality within key ETO process, namely supplier selection within the tendering process. Empirical cases presenting an insight in the quality of tools and resources at the different ETO stages within an IDEF model allowed us to describe the output quality in detail.

The assessment in isolation has limited potential, but with a series of scores for a number of activities within similar ETO projects, or when multiple projects were reviewed, it is possible to identify the generic root causes that were exposed to higher levels of uncertainty (Raham et al, 2003; Reid and Smyth-Renshaw, 2012; Simangunsong et al, 2012).

It has been argued within this paper that ETO processes encounter numerous uncertainties from a resource-based perspective (Gosling et al, 2009; Simangunsong et al, 2012; Gosling et al, 2015). In its current form, IDEF does not prescribe any specific set of tools to capture uncertainty, relying more on clarity of the representation (Soung-Hie and Ki-Jin, 2002; Kim and Jang, 2002; Lu and Liao, 2009; Ismail et al, 2010; Yigit and Allahverdi, 2010; Carvalho et al, 2016). IDEF is designed to be generic in structure, independent of tools relating to risk and process quality (Ismail et al, 2010). However, there is a contribution for the mechanism to categorise the output quality of resources within an ETO project, where key decision-makers can utilise the additional resources within the ETO project in order to improve the output of the activity. For example, creating greater transparency within the communication mechanisms supporting the collective learning across the project, which is fundamental to the reconfiguration of resources within ETO, where projects are often deemed as one off by their very nature (Hicks et al, 2000; Cameron and Braiden, 2004; Tsou, 2008; Gosling, Naim, and Towill 2013a; Gosling et al, 2015; Verdouw, 2011; Napoleone, et al, 2018). The authors have also identified numerous 'hotspots' in the ETO process which are often repetitive and thus provide key information regards the quality of the process. Lessons can be learnt from one project and ultimately support similar projects going forward.

The paper's contribution in proposition of a IDEF-QA approach has enabled managers to analyse the performance of their resources in far more detail, as opposed to adopting traditional approaches such as performance measures, or the more traditional methods of process models (IDEF, DFDs and SSADM, GRAI (Vosniakoss and Barla, 2006) in order to define the IDEF priorities (Bevilacqua et al, 2015). These process models, such as IDEF, are predominately used for representation and accreditation purposes, such as IS09000 quality management systems (Bing, 1999; Rashid & Ismail, 2007) and service quality (Bevilacqua et al, 2015). This study provides further insight which may help researchers and industrial practitioners adjust the way they utilise their existing process models (c.f. Koh and Gunasekara, 2006; Browning, 2010). This extended IDEF model, adopting the IDEF-QA concept, demonstrates the variations of quality within the context of an ETO supplier chain relationship in which the ICOMS, including tools, impact the output quality of the entire ETO process.

The adopted extended IDEF-QA approach, designed for the complexities of ETO uncertainty, aids those projects seeking to quantify the fit between their internal resources as the project evolves, or marginally eroding the output quality through inferior or underperforming resources. The underlying connections within such a resource/tools-based perspective, enables managers to identify such 'hotspots' within the ETO tendering process in which it is most vulnerable in terms of reliability and uncertainty, both internally and across the supply chain when tenders are being created or customised (Grötsch et al, 2013; Zolghadri et al, 2011; Gosling et al, 2013b;). The sample case study also contributes to the applicability of the extended IDEF approach, developing the IDEF-QA using a traffic light representation, (e.g. see Figure 6) in order to identify potential risks and uncertainties within the ETO process. The approach can be extended to suit other external issues and additional weighting factors associated with process performance and confidence levels, such as the reliability of suppliers with multiple contracts. However, one of the limitations of the IDEF-QA is the restriction of the time constraints of the research. The area of focus for future work will be to develop the approach further as ETO projects become more complex within ETO across supply chains. The efficient and systematic analysis of the design becomes an ever more important issue (Lu and Liao, 2009; Yigit and Allahverdi, 2010; Carvalho et al, 2016). The elements could also include: a module to satisfy a portfolio of templates for process modularity; a user interface to facilitate the capabilities through the notion of servitization; and a larger cross section of companies.

The IDEF-QA adopts a clear focus, in terms of assessing the quality of resources at a company's disposal, and the external factors that influence the decision making process. In terms of RQ1, the extended IDEF model demonstrates the capability of highlighting uncertainty within a complex process as ETO's tendering process. The IDEF-QA reflects on upstream activities and thus provided key information downstream, in order to establish the confidence of the process. For example, the initial installation and commissioning process within the ETO identified that performance data was currently unavailable to support the decision-making processes in project estimating, thus eroding the reliability of future tenders (Browning and Ramasesh, 2007; Zolghadri et al, 2011). Furthermore, the approach is based on sequentially assessing the quality of tools and resources. Each IDEF(0) activity box is often referred to as ICOMS within the IDEF structure. The IDEF-QA uses both a qualitative and quantitative approach to ascertain the output quality of a particular activity. To add to the development, the intension to present the IDEF-QA model through coloured attributes reduces the visual complexity of the model, thus providing comprehensive IDEF-QA map with an integrated traffic light system.

In terms of RQ2, the research supports the idea that an extended IDEF methodology can ultimately identify uncertainty within the ETO project or vulnerabilities within the supply chain (c.f. Gosling et al, 2009; Simangunsong et al, 2012; Gosling et al, 2015). Therefore, the extend IDEF model traces the root-cause of uncertainty being experienced within the ETO project and, as a result, can potentially support future projects by using the model as a marker of potential risk. Furthermore, risk analytics approaches, such as enterprise risk management (ERM), have emerged as an integrated approach to manage the risks an organization faces (Wu and Birge, 2016).

Through the adoption of IDEF-QA to project reviews and milestone monitoring, the company reduced the percentage of rework, resulting in an increase the number of units produced by 11%. A record high of 200 units a year, over a four-year period. Furthermore, within the case study company, the senior management team have since resolved a number of the issues mentioned above, addressing the absence of effective mechanisms to control the hand-over points across the core project milestones which caused additional conflicts of responsibility and ownership. As a result overall lead times were reduced from 22 to 20 weeks through monitoring the output quality within the process at the front end of an ETO project and developing more robust processes in their specification design, conceptual design and project planning stages, prior to the integration within their existing supply chain.

7 Conclusion

Our investigation makes a number of contributions. First, we bring together a source of different literature streams, in investigating ETO operational issues and the complexities in terms of the tendering process. Secondly, we revisit the existing literature on IDEF by providing a qualitative framework that assesses the resources that underpin key functions within the ETO process and projecting the output quality overall. Thirdly, our case reveals that IDEF-QA is not exclusively applicable to current projects but also supports future projects from a process perspective. Finally, we identify the additional opportunity for rethinking the contribution of IDEF; we revisit the presentation of IDEF through the IDEF-QA to understand how the output quality can be incorporated in an IDEF model. We believe that applying these concepts builds a theoretical approach by drawing on IDEF principles.

The use of the extended IDEF-QA provides a methodology to highlight numerous levels of uncertainty in the tendering process. This is often underutilised and suffers from incomplete and insufficient information, particularly within the front-end, context of resources and capabilities within the ETO supplier chain. It is hoped that this empirical research has contributed to refining the plethora of papers investigating the application of IDEF, with a focus within the complexities of ETO manufacturer projects. The intended IDEF-QA approach has presented some of the elements which will support both the development and further understanding the representation within the context of determining the quality of resources and the impact may disrupt the front-end process when engineering a new product to market, such as customised ETO pump design. We believe that this study provides an important contribution for researchers and practitioners by developing the notion of a reconciled ETO uncertainty through the utilisation of the IDEF-QA model to develop templates for complex ETO supply chains (c.f. Gosling et al, 2009; Simangunsong et al, 2012; and Gosling et al, 2015). The IDEF-QA model should help managers reduce the time and effort required for investigating uncertainty and risk by reflecting on the key stage indicators assessing potential drift in a project as a result of underperforming key resources and tools within a project.

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