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TOWARDS EMPIRICALLY-DERIVED GUIDELINES FOR PROCESS MODELLING INTERVENTIONS IN ENGINEERING DESIGN

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ABSTRACT
Task-network modelling approaches are widely used to understand and improve product development (PD) processes. The best-practice application of these tools is often presented prescriptively. This paper proposes that best-practice, and academic understanding, of PD process modelling can be further developed through an empirical approach, in which modelling tools are taken as given and practice is analysed in terms of how industry stakeholders use these tools. We argue this inductive approach can result in process modelling guidelines which explicitly recognise the challenges of modelling in industry. We thus analyse four cases of process modelling at Rolls-Royce plc and find that: 1) modelling is a social process of knowledge-creation; 2) effective modelling requires selection of the appropriate methods and tools at the right time; and 3) understanding the purpose of each interaction between participants in the modelling process helps to choose the best approach. To conclude we present guidelines to suggest which modelling approach should be used in which context, where context is described in terms of the purpose of a given modelling interaction.

Keywords: Design process modelling, process modelling practice, knowledge creation

1 INTRODUCTION
Process modelling plays an important role in the understanding, management and improvement of product development (PD) processes, including engineering design. A process model can be used: to visualise an existing or proposed process; to support project planning, execution and control; and as a tool to improve existing processes or to develop new processes [1]. There is an extensive body of literature describing a wide range of different process modelling approaches and the tools available to support them (see for example [1, 2] for reviews related to product development).
Engineering design processes pose particular problems for process modelling. Unlike many business processes, which are often sequential within a single business function, engineering design typically involves multiple parallel streams of activity performed by people across different disciplines. Moreover there are complex interdependencies between these activities and uncertainty about task sequencing and outcomes, which leads to iteration and difficulties in prescribing the exact process flow [3]. Consequently a number of engineering design specific modelling and planning tools and methods have been proposed [e.g. 4, 5-7]. In general these methods and tools are problem-focused. Following Maffin [8], Roelofosen *et al.* [7] propose that for project planning the methods and tools should be situation-specific instead. In this paper, we argue that similar logic should be applied to process modelling, i.e. that there is a need for guidelines which capture the contextual factors which define when different modelling methods and tools should be applied within a given process modelling intervention.
In other fields there is an on-going debate about whether methods and tools that will be used by practitioners can be developed through a purely top-down approach, i.e. from an analysis of the nature of the problem to be solved. For example, in the information systems (IS) field there is now an extensive body of literature exploring the various shortcomings of traditional, prescriptive, structured methodologies for IS design and development – in particular highlighting the need to better understand the sociology of the complex, knowledge-intensive group decision making involved in using these

tools in practice [e.g. 9]. This debate has led to the acceptance of bottom-up, empirically-led approaches as complementary to the top-down, problem-oriented paradigm for researching IS.
This paper reports on the first steps of investigating actual PD process modelling practice from this point of view. We aim to formulate an explanation for why modellers choose different methods and tools when modelling complex engineering design processes in industry. Building on the arguments of the IS researchers, we propose that these empirically-derived explanations can be used to develop detailed, context-sensitive guidelines which complement more prescriptive, top-down methodologies for process modelling interventions. The longer-term objective is to provide feedback to allow development of methods and tools which can better address the problems which emerge from how practitioners apply PD process modelling in an industry context.
The paper is organised as follows. Section 2 sets the context of the paper by discussing process modelling approaches in the engineering design literature and presenting a high-level model of knowledge-creation through process modelling. This model highlights the cyclic structure of the modelling process and its role in the overall modelling intervention – and highlights the need to explore this structure and the modelling episodes within it to develop practical guidelines for modelling support. Section 3 describes four case studies of process modelling in which the authors participated, which are used to achieve this. Section 4 discusses the methodology by which these studies were analysed. Section 5 presents the high-level findings, comparing the modelling approaches taken across the four case examples. Section 6 presents tentative modelling guidelines which arose from the case findings. The guidelines are context-specific, organised according to the modelling activity at hand and its objective in terms of the type of knowledge generated. Section 7 concludes.

2 BACKGROUND AND OBJECTIVES

2.1 Task-network Modelling of PD Processes – Notations and Tools

There are many different ways that PD processes can be represented and analysed, which can be broadly grouped into activity-based models, systems dynamics models, causal models and parametric models [1]. This paper focuses on diagrammatic task-network models, i.e. those which view a process as tasks with information flows between them, and represent this as a flowchart diagram.
Perhaps the most well-known diagrammatic task-network modelling notation is the PERT chart and related critical path analysis, which aims to assist managers by identifying those activities which have greatest impact on overall project duration, and which must therefore be carefully managed [10]. Pritsker extended this approach, introducing GERT simulation models which allow incorporation of iteration cycles [11]. More sophisticated notations such as Event-Driven Process Chain (EPC) implemented in professional modelling tools such as IDS Scheer AG's ARIS [12] have become widely accepted in industry. Other widely-used task-network notations include IDEF0/IDEF3 [13], various types of UML diagram, and Object Process Modelling (OPM) [14]. A number of other approaches have also been developed specifically for engineering design, including ADePT PlanWeaver [5] based on IDEF0, Plexus Modeller (no academic publications available), and Applied Signposting [15].
Various non-diagrammatic or semi-diagrammatic process modelling approaches have also been proposed in the engineering design literature. For example, Eppinger shows how activity DSMs may be used to identify an order of attempting tasks which minimises information feedback, and hence iteration [4]. Cho and Eppinger [16] propose a framework for project planning based on DSM simulation. Browning and Eppinger [17] discuss application of a similar simulation to evaluate alternative process architectures. ProNavigator [6, 18] provides a hierarchically-structured modelling and execution approach which allows processes to be described as 'process elements' taken from a library and nested within 'structuring elements'. These describe whether the 'process elements' they contain should be attempted sequentially, concurrently or iteratively.

2.2 Creating Process Models

There are thus many notations and tools available for modelling engineering design processes. However, choosing an appropriate notation is only one part of creating a process model. Creating large models of complex engineering processes typically involves a division of labour between modellers, who have expertise in knowledge elicitation and modelling, and the process domain experts, who are typically involved in performing or managing the activities being modelled. Given that any process model is a selective, abstracted representation of reality, there are, therefore, difficulties in deciding what information to include, what to leave out and how to represent this information in the modelling domain [19]. The role of the modellers is to bring their expertise in the modelling domain to bear on the process domain and bridge the gap between them. This requires them to elicit information from the process domain, represent it in the modelling domain and then reconcile the two.

Doing this effectively can require significant experience. We propose in this paper that novice modellers could be assisted by structured guidelines which capture this expertise, in particular to assist with identifying which modelling notations and elicitation approaches are most appropriate to particular circumstances encountered within the modelling process. To clarify the structure of this process, and thus position the type of guidance we propose, the following sub-section presents a high-level model of how knowledge-creation occurs through process modelling.

2.3 The Structure of Knowledge Creation through Process Modelling

Through a number of case studies we have developed a high-level model which begins to describe and structure the process of knowledge-creation through process modelling. Our model is shown diagrammatically in Figure 1. It distinguishes between *modelling stages* which are conducted to develop different types of process knowledge, *modelling cycles* which are revisited iteratively within each stage to converge upon a consensus model, and *modelling activities* which form part of each modelling cycle. The output from each stage is a form of process model; however, it is important to highlight that we consider the objective of modelling is not to create process models *per se*, but to create *process knowledge* in support of a given *intervention*. In this context, we define an intervention as the project a company undertakes to document, change, improve or automate a process; process knowledge as the understanding which must be gained to enable a successful intervention; and process modelling as the mechanism by which the knowledge is developed. In other words, the knowledge created through the process depicted in Figure 1 allows the modelling intervention as experienced by its participants to occur. This experience is composed of a sequence of *modelling episodes* (not shown) which divide up the intervention over time and may include several activities or cycles.

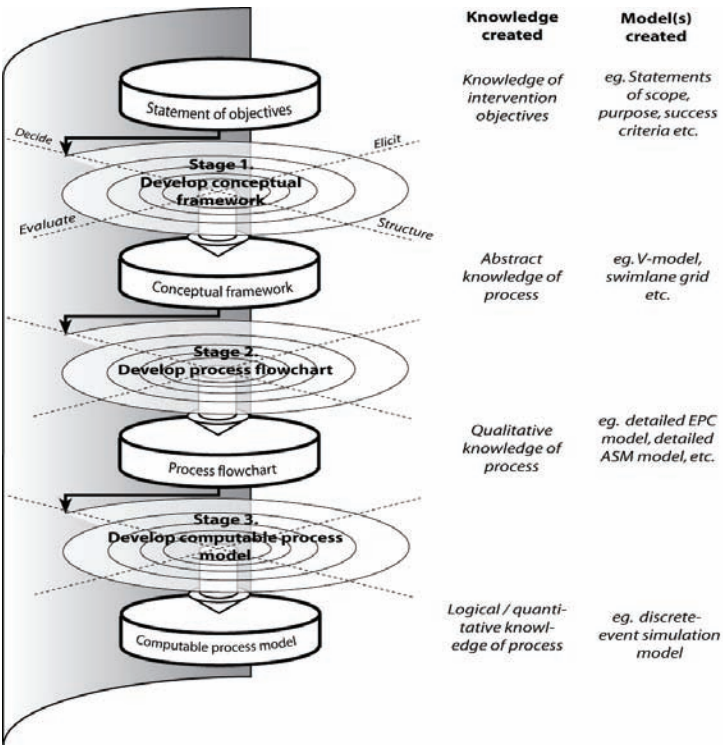

Figure 1. Our high-level approach to developing process knowledge through modelling

Progressive overall structure: stages

The knowledge-creation process begins with a statement of intervention objectives. This defines the boundaries of the process to be considered, the purpose of the intervention and, therefore, what type of knowledge is required and which process experts should be involved. Our model suggests process knowledge is then created in three increasingly concrete forms of: 1) abstract, 2) qualitative, and 3) logical/quantitative. This occurs through three stages, depicted as spirals in Figure 1:

1. **Develop conceptual framework.** A conceptual framework forms the basis for modelling activities in subsequent stages of the knowledge-creation process and assists elicitation, structuring and evaluation activities. The framework typically defines: a) the conceptualisation of the overall process structure, for instance as a V-model, waterfall, spiral or a grid of swimlanes in which tasks must be placed; b) the boundaries between different process experts' domains, which in turn, allows elicitation and evaluation activities to differentiate between individual concerns and those of multiple process experts; and c) the types of information which should be included (or excluded) from various parts of the model, for instance, the framework might stipulate that all design tasks should indicate the requirements they aim to satisfy.
2. **Develop process flowchart:** Develop knowledge of the low-level structure of tasks, information flows and other domains of interest. This is typically formalised using a task-network notation such as OPM [14], EPC [12], IDEF3 [13] or ASM [15]. Modelling activities conducted within this stage typically address the following objectives: identify tasks and their deliverables; locate the tasks in the conceptual framework; sequence the tasks; identify major decision points and iterations; interconnect tasks using the information they require and produce.
3. **Develop computable process model:** Elaborate the flowchart with further information relevant to the particular application of the model; for example, for process automation, which resources (e.g. people and tools) are used to perform a particular task. Beyond elaborating descriptive information in this way, developing an executable model requires the following information to be added to the descriptive model: task durations, number of people required and logic at the decision points in the model to replicate the process behaviour.

Knowledge is built up progressively; ideally each stage would be completed before moving on to the next. Nevertheless, in practice knowledge creation is a messy process. Iteration should therefore be expected across stages as increased knowledge leads to recognition that more information from a previous stage is needed or the output of that stage requires revision.

Iterative sub-structure: cycles, activities and episodes

As indicated in Figure 1, each stage is formed from multiple modelling cycles, each of which comprises a structured sequence of modelling activities. The overall knowledge-creation process may thus be viewed as a spiral structure, in which knowledge of the process and the model are progressively developed amongst the modellers and process experts. The modelling activities comprising each knowledge-creating cycle are:

1. **Decide:** What are the objectives of this modelling cycle? How will it be managed? Which stakeholders will be involved? What methods and tools will be used?
2. **Elicit:** The modeller obtains the information required to meet the cycle objectives. This can involve interviews, meetings, workshops or study of existing documentation.
3. **Structure:** The 'raw' information is structured to meet the cycle objectives and to integrate it with information developed in prior cycles, thereby helping create knowledge about the process. Structuring can include, for instance, creating new tasks in an activity network model or detailing a conceptual model.
4. **Evaluate:** The structured information is evaluated for fidelity and to determine whether it meets the objectives of this cycle and those of the overall stage. For instance, this could include discussion of changes to a model with the domain experts who participated in the elicitation activity. Evaluation may reveal that the stage is complete and prompt moving forward to the next. It could also prompt revisiting earlier stages.

These activities are described in abstract terms common to all modelling stages and interventions. However, as the process knowledge and model information content are progressively developed, these activities are instantiated in different ways. For instance, different elicitation approaches may be used, depending on the intervention objectives and the focus of interest at that time. The cyclic structure will often repeat several times at each level and is likely to involve various combinations individual and group interactions among the participants in the intervention, as well as deskwork, particularly by the modeller. Consequently the modelling intervention is structured temporally into a number of modelling episodes, each of which may incorporating one of more activities and even cycles and may occur quickly or over an extended time period. Whereas the distinction between stages, activities and cycles provides a useful abstraction to understand and analyse the structure of the modelling process, episodes are directly observable and can form the basis of an empirical enquiry of modelling practice.

Summary and additional points

Figure 1 provides a model of the knowledge creation process that occurs when process modelling is undertaken. It is not intended as a prescriptive model of the lower-level modelling process or the higher-level intervention which it enables. Rather, it clarifies the relationship between different stages, cycles and activities which occur during modelling, thereby highlighting the need to better understand the decisions made within the cyclic sub-structure in order to develop detailed guidance for inexperienced modellers.

In addition, the model is intended to convey that:

- Knowledge is built up in stages of increasing detail. The process will descend only to the stage required to match the objectives of the modelling intervention. For instance, many interventions will not require the logical/quantitative knowledge embodied in a process simulation or automation model. In such cases only the first two stages of Figure 1 apply.
- The knowledge-creation process applies whether the model is of an “as-is” or “to-be” process. It is rare that a model will be created “from scratch” without some other related models already existing, whether formally documented or not. In the case of “to-be” modelling it may facilitate the knowledge-creation process to model the “as-is” situation first. Multiple models may also be created concurrently.
- The knowledge-creation process is applicable to all forms of top-down process modelling, where the situation is progressively decomposed and elaborated in increasing detail. It is not specific to any one modelling notation or tool; rather, it is intended to express that different notations, methods and tools can be used within the process as appropriate to particular modelling episodes.

2.4 Objectives of this Paper and High-level Research Approach

The framework described above indicates the relationship between the progressive stages, iterative nature and cyclic structure of knowledge-creation through process modelling. However, this high-level model does not explore:

- **The great variation in models that may be produced**, for example, the scope of the process represented and the amount of detail included in that representation.
- **The different ways that process information can be gathered**, such as from existing documentation, one-on-one interviews or group workshops.
- **The different tools that may be used to structure information** and to document the model produced, including Post-it® notes, Microsoft Office tools such as Excel and PowerPoint, and specialist modelling tools such as ARIS [12], P3 [15], Loomeo [20] and ProNavigator [6, 18].

Even when following such a methodology, modellers are therefore faced with a wide range of possible ways to approach a particular modelling episode. The objectives of this paper are thus to explore the following research questions:

- *What are the differences in the approaches that modellers take to building process models in practice (such as different methods for gathering information and different tools for documentation)?*
- *Which factors, if any, can explain these differences?*
- *What are the implications of these findings in terms of pragmatic guidelines for process modelling interventions?*

The following sections explore these questions through an analysis of four case studies of industry practice, which is used to develop tentative guidelines for approaching activities within modelling episodes. The assumption underlying this approach is that there are substantive reasons for variations in the activities as conducted by practitioners – and that understanding these reasons by studying process modelling practice can form a starting point for developing detailed guidance for modelling episodes and the activities within them.

3 FOUR PROCESS MODELLING INTERVENTIONS IN ROLLS-ROYCE

Four case studies were conducted at Rolls-Royce plc., a world-leading provider of power systems and operates in four global markets: civil aerospace, defence aerospace, marine and energy [21]. The case studies were conducted within its Civil Aerospace and Energy divisions and involved modelling the early design processes of gas turbines either in the form of civil jet engines or for power generation on land. The four interventions are summarised in Table 1 and examples of the models produced are provided in Figure 2.

Table 1: Summary of the four interventions.

	IPAS	Energy Division	Integrated Process	Process Automation
Purpose of model	Improvement of civil aerospace conceptual design process	Visualisation (as-is) of prelim design process for knowledge transfer to another team	New (to-be) process for a new team merging eight different disciplines	Process automation across six design teams
Overall modelling approach	Interviews for data gathering. Group sessions for model refinement and validation	Two group working sessions	1:1 sessions for data gathering. Group sessions for model refinement and validation	Largely 1:1 interviews with each design team
Tools used	MS-PowerPoint for conceptual model. P3 [15] for modelling and simulation	Post-it notes for group sessions. MS-Excel for distribution	Post-it notes for process modelling	MS-Excel
Total time taken	2.5 years	3 months	In progress. 4 months at time of writing	In progress. 9 months at time of writing
Final model size	approx. 100 tasks	118 tasks	120 tasks (est.)	20 tasks per design team

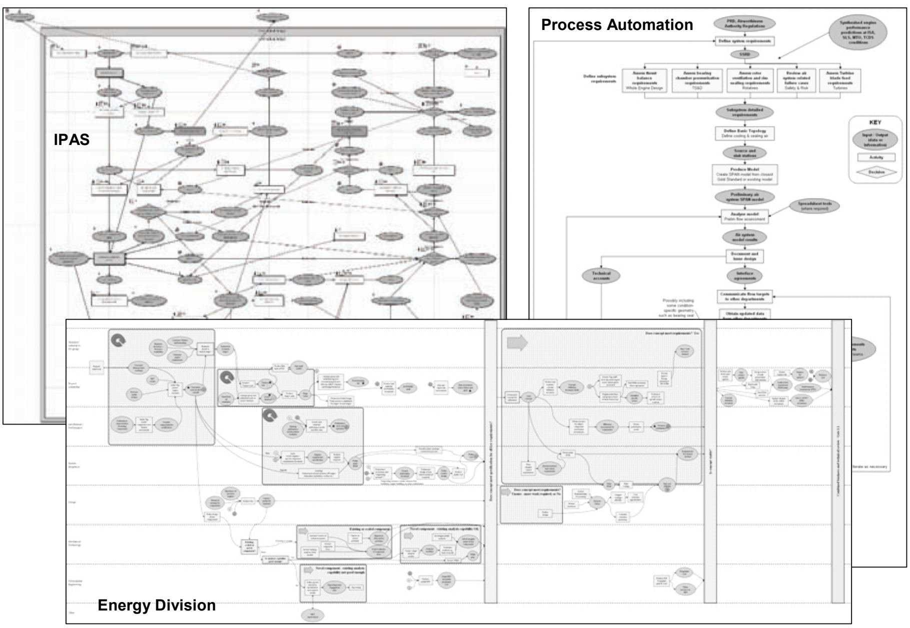

Figure 2. Example views of models created during the interventions

All four interventions followed the same basic development stages and iterative cycles described by the framework in Section 2.3. However, it was also clear that, within this framework, there is significant variation in how Rolls-Royce personnel approached process modelling episodes in practice.

The remainder of this paper analyses the four studies in more detail to explore the source of these variations and hence to tentatively identify more detailed, empirically-derived guidelines for modelling activities.

4 METHODOLOGY FOR ANALYSING THE INTERVENTIONS

The four cases were analysed using an inductive approach. This analysis started with the academic authors interviewing the Rolls-Royce modelling leaders. These interviews were semi-structured around the topics of: What was the model for? Which activities occurred? When did they occur, how long did they take, and who was involved? What were the information inputs to and outputs from each modelling activity? Based on these interviews, a timeline and narrative account was developed for each of the four case studies. General reflections and thoughts on the process modelling work were also extracted from the interviews. The narratives were then analysed following the principles of grounded analysis [22]. Following these principles, the text was reviewed and ideas and concepts within it were identified. For example, the following two sentences were coded respectively as being about *use of swimlanes* and *responsibilities*:

> *"He [one of the authors] talked about the different skillsets in the room and used this to add horizontal swimlanes on the wall. Everyone was allocated a swimlane to be responsible for"*

The elemental concepts identified were then grouped to generate higher-level categories for organising the analysis. For example, the *use of swimlanes* concept was placed in the category *tools and notations used in the modelling process*. The 16 categories which were generated are summarised in Table 2.

Table 2. Categories used to analyse the narratives.

When the work took place	The process modelled	Information/ other models available to the modeller	Number of tasks/ level of detail in the final model
Where the work took place	Reason for modelling (e.g. automation)	Tools and notations used in the modelling process	How the final model was used
Who did the modelling	Modeller's modelling experience	Sequence of workshops, meetings etc.	Evaluation of the modelling process and outcome
Who else was involved in the modelling process	Modeller's experience of the process domain	How long the modelling process took	Problems during the modelling process

According to the guidelines proposed by Miles and Hubermann [23], the four case studies were cross-tabulated against these 16 categories. After re-reviewing the initial coding, the table was populated with fragments of the text corresponding to the elemental concepts grouped within these categories. This table was used as the basis for identifying: *similarities* and *differences* between case studies, e.g. all the models included roughly 120 tasks after allowing that the process automation models cover 6 different disciplines; as well as *causality* between categories within and between case studies, e.g. the relationship between the modelling activities performed and the total time taken to finalise the model.
These comparisons were used to identify generalisable findings from the four cases and thus develop insights into how modelling episodes were approached within the knowledge-creation process. The causal links inferred between categories, based on the evidence gathered and a comparison with theoretical ideas in the literature – particularly those related to knowledge work – led to the explanations of these findings as presented below.

5 HIGH-LEVEL FINDINGS

This section reflects upon the analysis results to generate high-level findings, prior to presenting more detailed and context-specific guidelines for process modelling in Section 6.

5.1 Interactions between Modeller and Domain Experts during Modelling

Knowledge is created through interactions between modeller and domain experts and through the creation of the model artefact [c.f. 24], whereby knowledge from the various domains is integrated [25]. Two different types of knowledge sharing were observed to occur in the case studies: firstly between the modellers and the process experts; and secondly between the process experts themselves.
The objective of the interactions between modellers and experts is to create a boundary object [26] that acts as a communication mechanism between the various modelling participants. The case studies

indicated that in order for this to be effective, both modellers and process experts must have a certain level of common understanding:

- Process experts need to understand the modelling domain i.e. what is being represented and how this may be problematic. Even using a flowchart-based notation, which the authors thought would be relatively familiar to the process experts, in the case studies some domain experts struggled to distinguish between tasks and information objects. Others encountered great difficulty in expressing their work processes using this form of notation.
- Modellers need to understand a sufficient amount about the process domain in order to be able to assimilate the information that they receive from the process experts and represent this in the model that they are developing. This can be difficult, as modellers rarely have prior knowledge of the specific process domain before beginning an intervention.

The two-way process of knowledge transfer can be facilitated if individuals involved have knowledge of both domains. They can either act as knowledge brokers [27] or gatekeepers [28] between modellers and experts or actually produce parts of the model themselves. In addition, modelling will rarely start from a "blank sheet of paper". There are likely to be existing representations of the model held somewhere (even if tacitly in the experts' minds) and at some level (even if highly conceptual). Inevitably new models build on old. This may be a help or a hindrance, if old knowledge that is no longer relevant has to be unlearnt and discarded.

5.2 Interactions between Domain experts and other Domain Experts during Modelling

Besides the interactions with the modellers, interactions between the process experts themselves were found to be essential for them to develop a shared understanding of the entire process being modelled and to confirm and agree the information flows and dependencies between domains. This may create new knowledge about the process, which is the intention of to-be modelling interventions, and may be a by-product of documenting as-is processes. These group interactions also create buy-in to the modelling exercise through the shared discourse involved. One problem observed during the case studies was that process experts may adjourn from the modelling intervention or episode once they are comfortable that they understand what is going on and consider that their interests have been addressed – but before it is complete.

5.3 Role of Group Meetings

The case studies revealed that significant amounts of modelling work can be done by the modeller meeting with the process experts individually, or in small groups, for an hour at a time. However, the need for expert/expert interactions means that there must be some group meetings to develop cross-process domain knowledge and get agreement on the whole model from all stakeholders. The main issue requiring consideration when organising these meetings is to determine how much more should be attempted than is absolutely necessary to meet these objectives:

- **Pros of group meetings:** It may be difficult to get time from the process experts, so a long meeting involving most of the process experts could move the modelling exercise on significantly. Not only will the need for expert/expert interaction be addressed but it may also be – from the modeller's point of view – a more efficient way for them to interact with the group, rather than having to set up a series of individual meetings. From the process experts' point of view they may appreciate the opportunity to network with their colleagues.
- **Cons of group meetings:** On the other hand the more that the modeller tries to do in a group meeting the bigger the risks involved. Big meetings require greater organisation in order to be effective. Gathering information about the detail of the model in other people's areas may not provide useful information to other experts and so is potentially a waste of people's time. People may get de-motivated if the day is too long. These factors all add to the risk that the process experts may be dissatisfied with the conduct of the meeting and be less enthusiastic in future about continuing to participate in the modelling process.

Great care must, therefore, be taken to ensure that group modelling sessions are well organised and disciplined while recognising the tension between rigorously obtaining the information required and letting the discussion flow.

5.4 Choice of Tools and Notations

The choice of modelling tools is outwardly the most striking difference between modelling approaches taken across, and within the case studies. However, in many respects differences in tool choice are relatively easy to explain if modelling is recognised as a social process of knowledge creation. As in many other fields, such as information systems development, the tools chosen will be the ones that best suit the task to be performed and the preferences of their users [29]. The modelling tool used throughout a modelling intervention will almost certainly change from beginning to end – this was true in all four of our case studies. The authors' experience is that significant effort is not involved in manually transferring models between tools, compared to the total effort of the modelling intervention overall, especially given our experience that useable models should be kept to under 200 tasks.

The key factors influencing choice of tools and notations in the case studies appeared to be:

- **Speed/ease of model creation/modification.** This was a consideration whether the model was being documented in a meeting or "offline" by the modeller at their desk. Based on the case studies, only Post-it® notes were suitable for model creation in real-time in a group session.
- **Level of information to be recorded.** Post-it® notes were not good for capturing very detailed information. Specialist software tools were needed for process model simulation, but Microsoft Excel was adequate for descriptive, flowchart modelling studies of 20 or so activities.
- **Display size.** This needed to be big for a group session and was a particular strength of the Post-it® note approach. Where electronic modelling tools were used, typically this involved A0 plotter printouts of the model, possibly on multiple sheets, which the participants then wrote on to indicate their desired changes. Projecting models from a computer onto a wall was found to be unsatisfactory in most cases and likened to looking at the model "through a letter box".
- **Model sharing.** There was often a need for electronic distribution of the model and the means for multiple people to work on the model. This was a factor against the use of specialist modelling tools as they were not widely available to all the stakeholders involved in the modelling.
- **Personal preferences of the modeller.** This was a subjective factor, where there were a number of suitable tools (most notably between using Excel diagrams and P3 to construct models in the ASM notation, with some of the authors preferring one tool and some the other).

5.5 Summary

In terms of elicitation activities, the analysis indicated that generally individual interactions should be preferred, as they are more efficient for the process experts and lower risk for the modeller. However, group interactions are essential to develop shared understanding and overall agreement amongst the process experts. Given the issues of getting time with the process experts, when group sessions are arranged, there is a tendency to try to do as much as possible, risking losing engagement with some of the participants. Such sessions must therefore be well-prepared and well-facilitated.

Tools are chosen to best meet the needs of the modelling interaction. Post-it® notes can be very powerful in early group interactions, given the simplicity and ease with which they can be used. These advantages are soon superseded by the need for electronic storage and transmission. Specialist tools may be needed once the focus moves to elaborating the model in order to apply it to the solution of a specific problem. There appears to be no major impediment to modellers switching between tools as they develop the detail and sophistication of models.

Throughout it is necessary to recognise that modelling is a social process which has to meet organisational conventions. The knowledge creation that takes place in these interactions has to be incremental and contingent (the model may change the process and vice versa). Modellers have to take care not to try to gather too much information at one time or the wrong level of information too early. The knowledge of the modeller and that of the participants has to increase together in order for the modeller to request the appropriate information and the participant to provide it.

6 GUIDELINES FOR PROCESS MODELLING ACTIVITIES

A number of tentative guidelines were developed from the analysis presented in this paper and are summarised in Table 3. The guidelines are organised according to a three-dimensional classification scheme that indicates the context in which they should be applied. The first two dimensions, activity and stage, refer to the structures of the descriptive model described in Section 2.3. The third dimension, 'knowledge creation objective', refers to the purpose of the interaction between modeller and domain experts and the type of knowledge sought through that interaction.

Table 3: Guidelines for Process Modelling Activities

Activity	***Stage***	***Knowledge creation***	**Guideline**	**Rationale for Guideline**
Elicit	*Develop conceptual framework*	*Modellers learn about process domain*	Start with individual interviews to determine the objectives, scope etc of the model	Most efficient way for the modeller to start to learn the process domain
Elicit	*Develop conceptual framework*	*Modellers learn about process domain*	Gather information widely to start with (and then focus down)	Difficult to determine from the outset what and who should be included in the modelling process
Elicit	*Develop process flowchart*	*N/A*	Estimate upfront how large/ detailed the final model will be (at R-R this was about 120 tasks in all 4 cases)	Helps the participants to determine if the tasks are being specified at the right level of detail
Elicit	*Develop process flowchart*	*Modellers and process experts develop model*	Start stage with a group session using Post-It notes to elicit the task structure	Establishes common understanding of the model content and structure. Builds enthusiasm for future participation.
Elicit	*Develop process flowchart*	*Modellers learn process detail*	Use interviews to elaborate the detail in the process model	Most efficient way to gather specific information from the process experts
Elicit	*All*	*Modellers learn process*	Prefer interviews for elicitation	Interviews were effective for going into detail on specific points.
Structure	*Develop conceptual framework*	*Modeller and process experts develop model*	Conceptual framework should fit on a single MS-Powerpoint slide	Clarifies what information is needed from whom and why. Must be simple for all stakeholders to understand.
Structure	*Develop process flowchart*	*N/A*	Transfer model to electronic media (could be MS-Excel or a specialist modelling software, depending on availability)	Needed for electronic distribution and facilitates revision
Structure	*Develop process flowchart*	*Both develop detailed knowledge of model*	In group sessions, use large print outs of the model that people can write on	Encourages participation in revising and validating the model
Structure	*Develop process flowchart*	*N/A*	Do not expect to be able to model by simply combining existing models and process fragments	Models are built for specific purposes and existing models may need to be reworked
Structure	*Develop computable process model*	*N/A*	If transfer process model to a specialist simulation tool, maintain the process flowchart version in parallel (if this is not supported by the simulation software)	Development of the computable version is likely to lead to model changes. Computable versions may not be as easy to understand as the flowchart.
Structure	*All*	*N/A*	Use the modelling tools most appropriate to the job in hand	Higher quality interactions with the process domain experts compensate for time spent transferring models between tools
Evaluate	*Develop conceptual framework*	*Modellers and process experts develop model*	Validate conceptual framework in a group session involving key process stakeholders	Gains buy-in for, and encourages ownership in, subsequent stages of model development
Evaluate	*All*	*N/A*	Prefer group sessions for evaluation	Group meetings were essential to get consensus and agreement amongst multiple participants
All	*All*	*N/A*	Build the model in stages/ small steps	Process modelling involves incremental learning by both modellers and process domain experts
All	*All*	*Process experts learn about others' processes*	Concentrate on the interfaces between different disciplines (and assume most domain detail can be "black-boxed")	Most value for the process domain experts comes from understanding the relationships and information flows between their different domains
All	*All*	*N/A*	Allow sufficient time (both in and between meetings)	Process domain experts are busy and it is difficult to get their time
All	*All*	*N/A*	Prepare for and conduct meetings well	Use the limited time available from process domain experts as efficiently as possible.
All	*All*	*N/A*	Work hard to maintain the process domain experts involvement and enthusiasm throughout	Experts are usually volunteers and will withdraw from the modelling process if it is not providing them with value

7 CONCLUSIONS

Process modelling plays an important role in the understanding, management and improvement of product development processes, however relatively little literature in the engineering design field has analysed in detail how process models are developed in practice. This paper has argued that such an empirical analysis of modelling practice can help develop guidelines for modelling which reflect the problems faced by domain experts while applying tools and methods. We propose that these guidelines could complement existing, prescriptive methodologies for modelling, by formulating process modelling expertise in a way which addresses the problems as perceived by domain experts who are not necessarily experienced in process modelling methods. A number of tentative guidelines were developed based on analysis of four interventions in Rolls-Royce using a task-network modelling approach. This represents a very small sample of modelling interventions and, therefore, the guidelines shown above are presented as preliminary findings of an ongoing research programme. The main contribution of the paper is presented as the approach to developing these guidelines and the framework and descriptive model within which they are organised.

To summarise, the main contributions of this paper are:

- The need for empirically-derived guidelines for modelling to complement top-down, prescriptive methodologies was highlighted and an approach to developing such guidelines was presented.
- A model of process modelling as a method for knowledge-creation was presented and described in detail. The model highlights the relationship between progressive, iterative and cyclic structures alongside different activities and episodes which occur within the modelling process. It provides a conceptual framework for analysing PD process modelling and knowledge creation processes in depth.
- Four case studies of process modelling practice were discussed and analysed using a grounded analysis technique. This analysis resulted in high-level insights alongside more concrete guidelines which could support decision-making within the modelling process. The guidelines are tentative and it is recognised that further case studies and ongoing reflection are required to fully detail the empirical perspective of PD process modelling which we start to explore in this paper.

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