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WHAT ARE THE CHARACTERISTICS OF ENGINEERING DESIGN PROCESSES?

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ABSTRACT

This paper studies the characteristic properties of Engineering Design (ED) processes from a process modelling perspective. In a first step, we extracted nine characteristics of engineering design processes from the literature and in a second step validated the findings using results from our survey among academic and industrial ED process modelling experts. In a third step, we added a further nine characteristics from personal experiences in the Language Engineering Domain to capture the pragmatic perspective. We arrive at a comprehensive set of 18 characteristics grouped into 6 challenges for process modelling in the engineering design domain. The challenges process modelers need to address when using and developing process modelling approaches and tools are: *Development*, *Collaboration*, *Products & Services*, *Formality*, *Pragmatics*, and *Flexibility*. We then compare the importance of elicited and suggested challenges and characteristics within engineering design with software engineering and business process modelling and discuss similarities and differences.

Keywords: product development, design process modelling, business process modelling, process model, requirement elicitation

1. INTRODUCTION

Product development in engineering domains is an important organisational capability and can be a major competitive lever for firms. In general, one way to represent, understand, engineer, manage and improve product development (PD) is by taking a process-perspective, and in particular by using process modelling and creating process models [e.g. 1,2,20]. Process modelling as an activity tries to capture patterns that describe the behavior of processes. Process models are an essential part of process management and a great variety of process models can be found in literature. Process models are useful for researchers, practitioners and educators alike, for example, as they support problem-solving [3], they aid decision-making [4], they provide a common platform for communication [5], they are used for a number of purposes, e.g. project visualization, project planning, project execution and control, continuous improvement, organisational learning and knowledge management purposes [6], and they can be utilized to identify requirements for acquisition of software [7].

There are several domains that use process modelling, e.g. product development/engineering design, software engineering, and business process management, and there are a number of approaches and (graphical) process modelling notations. Similarities and differences are not always transparent and there are a variety of (competing) approaches even within domains. For an overview of extant process modelling methodologies in engineering design, software engineering and business process management see, for example, [1,2,7]. Given the differences in scope and intent of the above-mentioned comparisons, a synthesis of criteria is not straightforward and it is therefore not easy for practitioners to navigate existing approaches and to decide on their utility for modelling specific engineering design processes. Trying to arrive at an answer as to what it is that a process modelling approach needs to be capable of in the context of engineering design, the primary research question of this paper, therefore, reads: *What are the characteristics of engineering design processes?*

This paper is aimed at researchers and practitioners in industry who are using and seek to develop process modelling approaches. The objective of this paper is to elicit and suggest engineering design process characteristics as a basis for defining requirements for an ideal engineering design process modelling approach. In what follows, we use the term Engineering Design (ED) process to differentiate between engineering design and software engineering. The term is, however, synonymously used with what other authors have termed PD processes.

2. METHODOLOGICAL PROCEDURE AND STRUCTURE OF THE PAPER

Research reported in this paper contains five different parts. Firstly, we conducted a literature study to elicit characteristics of Engineering Design (ED) processes. We found nine different candidates (Section 3). For that, we followed a Grounded Theory-inspired procedure as we inductively generated candidates based on what we found in literature, rather than deductively applying a pre-defined 'coding-scheme' to the literature. Secondly, we ran a survey among ED process modelling experts from academia and industry to validate and prioritize characteristics found in literature (Section 4). We added a further nine characteristics of process modelling notations and tools as known from language engineering (Section 5). All 18 characteristics are grouped into six challenges of three characteristics each. Finally, we discuss elicited and proposed characteristics compiled so far for different process modelling domains, namely engineering design, software engineering, and business administration and describe implications of the work for defining requirements for process modelling approaches (Section 6). We conclude the paper in Section 7 with a summary and suggestion for further work. This procedure is summarized in Figure 1.

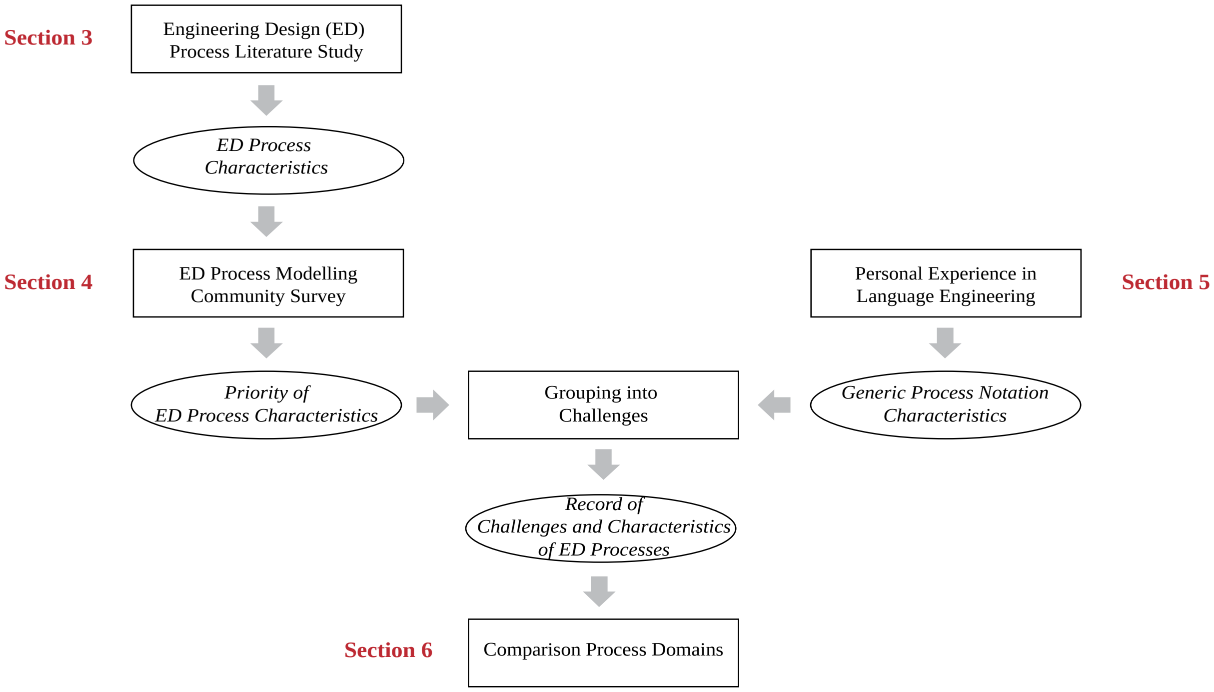

Figure 1: Structure of work reported in this paper (Petri Nets-inspired notation)

3. ENGINEERING DESIGN PROCESS LITERATURE STUDY

Nine characteristics were elicited from an engineering design literature study and later on grouped into three challenges. They are listed in Table 1 overleaf and described in what follows. The boundary between characteristics is fluid. A small number of literature references was selected due to formatting instructions of this conference.

3.1 Challenge 1: Development

The Engineering Design (ED) process is always concerned with the development of solutions for a unique set of constraints and boundary conditions. Although development rarely starts from a blank sheet of paper, often, solutions are new.

- ***Ill-defined:*** It is the very purpose of ED to develop and create a solution where there have only been constraints and desires before and precise goals are unknown at the start. It is in the nature of development processes that there are elements of uncertainty in their outcome [8]. If the result were completely defined at an operational level of detail, there would not be a need for creativity in the sense of a different/new solution. Often, the need or problem is understood whilst the solution is generated and evaluated, and often, there are rolling targets. It is in this sense that ED problems are described as ill-defined (e.g. [9-11]).

- ***Iterative:*** A common characteristic of all creative activities is that they are iterative by nature: various alternative paths and successive versions have to be pursued, elaborated, compared, fused, split, improved, evaluated, rejected, and reconsidered so that in the end, the design space for a given set of constraints has been sufficiently explored to find a solution. The structure affording such a meandering search process is described as iterative (e.g. [12]).
- ***Complex:*** ED processes, such as development of airplanes, jet-engines, automobiles are highly complex [13]). *"The challenge for many designers is to maintain an adequate overview of a complex emerging product and its equally complex design process"* [14, p.3]. There are many different factors, such as the nature of human cognition and creative problem solving that are still not well understood today. There are many variables that require optimization of high-dimensional spaces of options. There are complex interactions of time-coupled systems with non-linear dynamics ("deterministic chaos") that defy conventional prediction and approximation methods. Together, these factors equip ED processes with a complexity that immunizes them against brute-force approaches.

Table 1: Challenges and ED process characteristics

Challenge	Engineering Design Process Characteristic
Development	Engineering design processes are • complex • iterative, and • ill-defined.
Collaboration	Engineering design processes are embedded in an ecosystem of processes with multiple interdependencies and interactions between • different processes, • people involved, and • processes and organisations.
Products & Services	Engineering design processes are constrained and influenced by • the physical nature of the artifact developed, • economic and market constraints, and • legislative and regulatory constraints.

3.2 Challenge 2: Collaboration

Virtually all instances of ED processes require the collaborative effort of many people. Most design instances involve a great number of people, distributed over space, time, and organisations. Often, participants exhibit widely differing skill profiles.

- ***Process-process interactions:*** *"Most engineering design processes are intertwined with other engineering processes, embedded in other business processes in the organisation, and linked to a number of supplier companies´ process."* [14, p.22]. No process is isolated from triggering, supporting, or ensuing processes which are more or less well-defined and standardized in an organisation. ED processes are embedded in an ecosystem of processes with multiple and complex interdependencies with positive and negative feedbacks.
- ***Process-organisation interactions:*** Processes are epiphenomena of the organisations executing them. Besides the 'official' process and the 'official' organisation, there are always informal structures, traditions, and external influences that perturb ED processes. Organisations executing these processes are often collaborations of virtual development networks. Automotive supply chains are examples of global process-organisation interactions (e.g. [13]).
- ***People-people interactions:*** *"The design of a modern product, such as a car, requires the collaboration of a multi-disciplinary team"* [14, p.5]. Beyond the sheer size and ubiquitous fundamental issues implied in cooperation between humans, the global scale, the inherent complexity, and the creative nature of ED processes adds influences to the communication process that transcend the limits of existing terminology and methods [15]. Also, many engineers employ a visual mode of information processing rather than a verbal mode which could be better supported by today's telecommunication technology.

3.3 Challenge 3: Products and Services

Companies move from selling physical products or hardware alone to offering services and offer product-service systems. This can, for instance, be seen in the aerospace industry in moving from selling gas turbine engines by the unit to providing power-by-the-hour.

- ***Physical nature of engineering artifacts:*** *"The product is the strongest constraint on its own design process"* [14, p.9]. A process supports the development of a product or service and the structure of the process should therefore ideally be closely connected to the product architecture [16]. The physical nature of many the artifacts of ED processes adds specific classes of constraints. For instance combinations of electrical, physical, mechanical, and space restrictions, may sometimes be traded-off against each other, while at other times they require global optimizations.
- ***Economic and market constraints:*** Companies are looking for an appropriate design process to achieve the desired product within given time, cost and resource constraints. ED processes are always embedded in economic contexts. *"Tendering agreements define timescales and budgets and often impose harsh penalties for late delivery"* [14, p.9].
- ***Legislative and regulatory constraints:*** Many engineering artifacts are subject to stringent regulations from different sources that need to be addressed in the ED process. For instance, technical standards like DO178A imply specific forms of tracing and legislation on safety and environmental certifications influence engineering design processes (e.g. [17]).

4. ENGINEERING DESIGN PROCESS MODELLING COMMUNITY SURVEY

To draw on additional sources of information for eliciting characteristics of ED processes and to comment on our findings, we sent a questionnaire to 22 experts from the engineering design process modelling community. Experts queried are from 19 different institutions; eight from industry and 11 from academia. We presented ED process characteristics assembled from the literature study to the poll participants and asked them to assess importance of each criterion on a four-step Likert scale ("very important", "important", "somewhat important", "not important", which was encoded as 4 to 1). We encouraged participants to provide additional free form comments. Of the 22 ED process experts contacted 15 replied which gives a feedback rate of 68%. Those participants who replied are affiliated with six different industrial and 6 different academic institutions. One participant did not answer our questions but gave summary comments. These answers were excluded from the quantitative analysis. All but one answering participants were male.

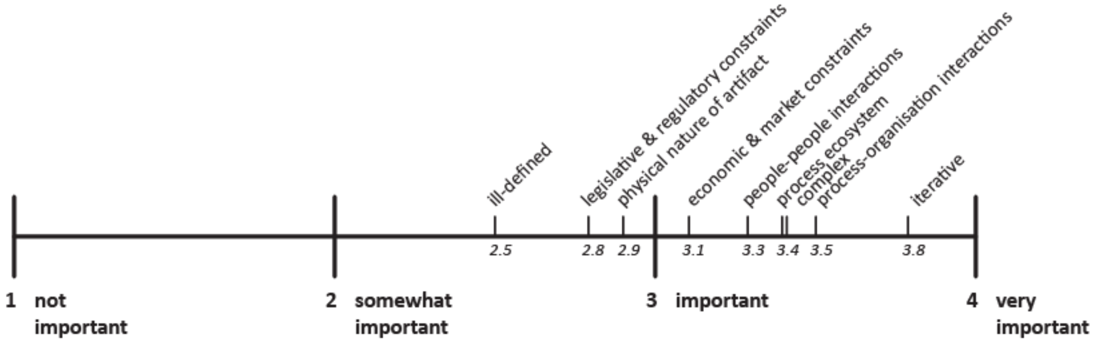

Figure 2: Importance of ED process characteristics (N=15 process modelling experts)

Our survey exhibited very strong support for the results of our literature survey (see Figure 2 and Table 2 overleaf). All characteristics we suggested to the participants are strongly supported, and there is also a clear hierarchy among the characteristics (see Figure 2). We thus conclude that the characteristics listed above in Table 1 are indeed the characteristics of ED processes. It should be noted that except for clarification questions, no participant suggested additional or different criteria for ED processes. 20 comments clarifying and agreeing with individual characteristics were given by six different people. The three disagreeing comments were made by only one participant who also gave the least overall support to all characteristics suggested in this paper.

Table 2 shows the descriptive statistics for all characteristics. The standard deviation is generally small, and smallest for the two characteristics with the most and the least support among the survey participants. Using R's t-test, we find that results for six out of nine questions are significant. Only replies to the third and the seventh question (ill-defined and physical constraints) are not and the answers to the ninth question may or may not be statistically significant.

Table 2: Support by expert panel for ED process characteristics (comments were optional)

Statement	**Mean**	**Median**	**Std. Dev.**	**Signifi-cance**	**Comments**	
					agree	**disagree**
1) Engineering Design (ED) processes are complex.	3.50	4	0.85	***	2	1
2) ED processes are iterative.	3.71	4	0.47	***	2	-
3) ED processes are ill-defined.	2.54	2	0.52		2	-
4) ED processes embedded in an ecosystem of processes.	3.29	4	0.83	**	2	-
5) ED processes have process-organisation interactions.	3.43	4	0.94	**	2	-
6) ED processes have people-people interactions.	3.36	4	0.93	**	2	-
7) ED processes are constrained by physical nature of artifact.	2.86	3	1.17		3	1
8) ED processes are influenced by economic and market constraints.	3.00	3	0.78	*	3	1
9) ED processes are influenced by legislative & regulatory constraints.	2.86	3	0.77	.	2	-
Average/Sum	**3.20**	**-**	**0.81**	**-**	**20**	**3**

With significance levels: 0 < *** < 0.001 < ** < 0.01 < * < 0.05 < . < 0.1 ‘ ’ 1

The characteristic “ill-defined” clearly enjoys the least support, although this property is discussed extensively in the literature. There are two possible explanations for this observation. Firstly, it could be that being ill-defined is indeed the least important characteristic of the properties of ED processes, yet it might be unique to ED processes in comparison to other domains which would explain the impact it has in the EDP literature. However, at least the software engineering process domain shares this property (see Table 4 and the discussion in Section 6), which makes this explanation appear unlikely to be verified. A second explanation might be that in the absence of a specific artifact suggested by us in the survey, people associated different definitions with the term. We tend to adopt the second interpretation since in our survey there was little explanation on the statements, and the only clarification question any participant asked was on this characteristic. That would mean that being ill-defined may actually be a more important characteristic than suggested by our data.

The characteristic “iterative” enjoys by far the strongest support. It attracted comments, such as:

- *“Yes, almost always iterative”*, or
- *“Yes, it's often difficult to plan for first-time-right, i.e. without iterations in the process”*, and
- *“Requirements change, design ideas change/improve, what is manufacturable becomes better understood...but [assertion without proof!] I still feel that a well-designed design process could remove much of the iteration if it was truly desired.”*

We interpret that this is an expression of the perceived inventiveness of ED processes which leans towards search and repetition.

None of the participants suggested any additional characteristics beyond the list provided. Participants provided general comments, such as *"This is a very interesting set of questions"* and *"As far as your questions go - wow! […] I certainly think this is an excellent list of issues"*. However, participants also commented on a methodical point, as highlighted by the following quote which we received three times in different wordings *"I think […] the questions are a bit too general to easily make sense of the answers. For instance: important to whom and from what perspective? Also, what sort of engineering design are we considering?"* This is a methodological problem inherent to questionnaires. However, since our statements are based on a grounded theory-inspired literature study, we feel that our initial questions are justified.

5. LANGUAGE ENGINEERING IN PROCESS-FOCUSED DOMAINS

Up to this point, we have elicited characteristics of ED processes which need to be addressed in any ideal process modelling approach. However, there is also a large number of pragmatic factors that strongly influence the viability of process-focused approaches. One of the authors of this paper has worked in these industries for several years, providing ample experiential evidence that these factors are indeed significant, but are also more or less independent of the application domain as such. That is to say that while these factors are relevant and, in any practical setting crucial, they are rather similar in different process domains, such as software engineering processes, and business administration processes, suggesting that these pragmatic factors are also valid and applicable in the engineering design domain.

Such factors include availability of tool support and its quality, availability of additional services and instructional material, and issues related to evolvability and customisability of the approach.

Table 3: Challenges of ED processes and factors influencing a process-focused approach

Challenge	Factors influencing a process-focused approach
Formality	Cost-effectiveness of process-focused approaches builds on • automatable sub-activities, • conceptual clarity, and • formal semantics.
Pragmatics	Applying process-focused approaches in practice requires • a supportive eco-system, • practical tools, and • a task-adequate concrete syntax.
Flexibility	Using process-focused approaches in the large scale needs support for • scalability, • customisability, and • ensured evolution.

5.1 Challenge 4: Formality

Many steps in the ED process benefit from or inherently require automated support (i.e. through computerized tools). Therefore, ED process languages must afford formal structures and preferably be defined in an explicit manner.

- ***Automatable sub-activities:*** In the face of cost, quality and schedule pressure, we need all the help we can get and so there is a great demand for automated solutions for individual steps or sub-activities in the ED process. For instance, dynamic simulations, static analyses, generation of task/part lists, workflow execution and so on are feasible today, though most methods and environments support only a small selection of these. Also, the support provided is often given as individual steps rather than in the form of an integrated tool chain, that is, there are media gaps, data incompatibilities, and similar impediments to the workflow in existing solutions. In software engineering, a similar situation has given rise to the CASE movement of the 1980's, demanding interoperability between software engineering tools. This has resulted in standards like the ECMA's Portable Common Tools Environment (PCTE) , and mature technologies for component interaction. In business processes, there have been multiples attempts to standardize workflow definition and execution with mixed success, one of the latest approaches being Business Process Modelling Notation (BPMN).

- ***Conceptual clarity:*** While humans are to a certain extent capable of disambiguating different usages and guidelines based on context and common sense, automated tools need clear cut distinctions between and detailed definitions of minute details within notions and concepts of Engineering Design Process Notations (EDPNs). Otherwise, any tool implementation will introduce a new EDPN dialect with associated usages and limitations. Therefore, conceptual clarity is indispensable in an ED process approach. The state of the art would be an explicit meta-model defining the abstract syntax.
- ***Formal semantics:*** Technically, the basis for interoperation and integration of process activities, processes, and organisations requires standardization of interfaces and formal definitions for data structures, interactions, and life cycles. However, the formal structure is only supporting the core usages of the EDPN, so that it must not get in the way of the engineer when not needed, e.g. during modelling. Providing an implementation (“semantics by compiler”) is not sufficient to achieve this goal. Rather, a mathematically rigorous semantics as a mapping from the abstract syntax into a formal domain, such as Petri Nets, dependency matrices/graphs, or process algebraic expressions, is necessary.

5.2 Challenge 5: Pragmatics

Besides the challenges inherent in the application domain, there are also challenges arising from the realm of modelling as such. These challenges might be considered mundane and secondary, but experience in other domains that have been studied for a longer time than ED processes demonstrates that these considerations are just as critical and scientifically interesting, even though they may be arising only after other considerations have been dealt with.

- ***Supportive Eco-System:*** In order to unfold the full degree of practical benefit, there must be an ecosystem of supportive resources, beyond just tools. For instance, established practices, consultancies, literature, and established academic teaching will be necessary. If these are not readily available, introducing an approach into a company will be very expensive and difficult, irrespective of other qualities of the approach. When a supportive eco-system is available even an approach that is inferior in terms of, say, conceptual clarity or formal semantics can be acceptable or even superior when looking at the bottom line.
- ***Practical Tools:*** Probably the first practical need in any ED process approach will be the availability of high-quality tools. As the history of modelling notations in the SE domain has clearly shown in the case of UML, a network effect about notations can lead to a wealth of tools of unprecedented quality and functional scope in a few years.
- ***Adequate Concrete Syntax:*** Every process modelling approach must use some modelling notation, be it visual or textual. While the expressiveness of such notations has been studied frequently, their adequacy for given tasks in terms of the cognitive load or help it provides is still largely an open issue. There are approaches concerned with generic quality criteria for visual languages [18] or language/environment systems [19], but to the best of our knowledge, there are no studies concerned with process modelling notations.

5.3 Challenge 6: Flexibility

Similar to the practical issues related to modelling addressed above, there are practical issues related to the modelling language as such. Issues on this level are commonly referred to as Language Engineering.

- ***Scalability:*** An EDPN is more useful if it accommodates many levels of product/project size and duration so that investments in the ED process notation, tool-chain, and development process ecosystem offer a higher return. Also, the reuse and learning across different application conditions will induce a higher general capability level.
- ***Customisability:*** It is generally true that general purpose languages have a number of important advantages over domain specific languages. However, there is always a gap between any general purpose language and a concrete customer, project, purpose, or domain, either in the sense that some concepts or notations are missing, or that many concepts and notations are unused. The former will lead to complex and error-prone work-arounds (“patterns”), the latter may confuse and overwhelm users and management and so impede adoption. Either way, there is always almost

some demand for customizing a language and tool environment, through addition or removal of concepts/notations or features.

- ***Ensured evolution:*** The lifecycle duration and scale of investment of major ED processes requires at least a similar scale for the ED process notation and tools; investments in the tool chain and supportive structure easily reach the investment in new products in the domain. Their effect on the ED process can hardly be overestimated, both in terms of potential loss of productivity and quality, as well as overall process maturity. Therefore, a continuous and controlled evolution of an EDPN is a strong argument in favor of using it.

6. DISCUSSION: DOMAIN COMPARISON AND IMPLICATIONS

6.1 Domain comparison

We now discuss whether the challenges and characteristics found for engineering design processes are equally important and prevalent in other process modelling domains, in particular software engineering and business administration. We base our analyses on personal industry experiences. As far as the challenge ***Development*** is concerned, software engineering processes are rather like ED processes, whilst most business administration processes are much less complex, iterative and ill-defined. Of course, there are also more complex processes in business administration e.g., those concerned with product development, that are more like ED processes or Software Engineering processes, but those are typically not subject to business process modelling and administration. In terms of ***Collaboration***, unsurprisingly perhaps, all three domains exhibit similar characteristics. These characteristics might be intrinsic to the processes perspective. Looking at ***Products & Services***, in the software and business process domains most artifacts are not physical, or their physical nature is irrelevant. Entities like source code, contracts, or payments are constrained only by conceptual frameworks, making them much more complicated and challenging to validate than physical entities. The challenge ***Formality*** exhibits the strongest difference between the modelling domains considered. Software Engineering deals with a very high number of artifacts of high complexity and formal structure, where even the most minute mistakes are fatal. This has led to an unprecedented degree of process support by sophisticated tools like IDEs and modelling tools providing a degree of automation and integration not found in other domains. ***Pragmatics*** and ***Flexibility*** as challenges derived from Language Engineering are similar for all three domains considered. Table 4 summarizes this discussion, shows the large similarities between the three domains and highlights the differences.

Table 4: Comparing the challenges and characteristics for three major process domains

Challenge	Characteristic	Differences in Software Engineering	Differences in Business Administration
Development	Complex	-	usually quite simple
	Iterative	-	rare
	Ill-defined	-	well-defined
Collaboration	Process-Process-Interaction	-	-
	Process-People-Interaction	-	-
	Process-Organisation-Interactions	-	-
Products & Services	Physical Nature of Artifact	artifacts are rarely physical	mostly irrelevant
	Economic and Market Constraints	-	-
	Legislative and Regulatory Constraints	-	-
Formality	Automatable Sub-activities	much more important	much less important
	Conceptual Clarity	depends on level of detail	less important
	Formal Semantics	much more important	unusual
Pragmatics	Supportive Eco-system	-	-
	Practical Tools	-	-
	Adequate Concrete Syntax	-	-
Flexibility	Scalability	-	-
	Customisability	-	-
	Ensured Evolution	-	-

Table 4 shows that today’s business process modelling approaches may lack the expressiveness needed in engineering design: the characteristics “iterative” and “complex” are ranked as first and second in importance for ED (see Figure 1), but are not usually shared by business processes. Thus, a perfectly valid business process modelling notation may exhibit shortcomings in this area, as compared to the requirements of ED process notations. Software engineering process approaches on the other hand do not share this shortcoming, but may lack the ability to capture and model the physical nature of artifacts in the process. However, the high degree of automation and tool support found in Software Engineering processes far exceeds current tools in other process modelling domains. Thus, it can be expected that techniques and approaches developed to support SE processes might also prove to be useful for future ED tool development.

Our elicited and suggested selection of challenges and characteristics of engineering design processes stem from three sources: a literature survey, an expert survey, and personal experience with language engineering in industry from one of the authors. Industry experts answered based on their experiences in the oil- and gas, aerospace, and automotive industries – examples which might differ when looked at in detail. Experts in academia clarified the context within which their answers need to be read and suggested provision of context information for our questions. Pointing to the absence of a tightly focused research community in language engineering, we nevertheless will have to point to a certain bias concerning those challenges and characteristics suggested based on personal experience.

6.2 Implications for research and industry

We have listed challenges and characteristics of engineering design processes based on surveys of the literature and academic and industry experts from the engineering design process modelling community. Our findings show a consensus on characteristics of ED processes. This may lead to a relevant and valid set of criteria for selecting an ED process notation or tool. One of the survey participants commented on the selection as follows. “*I certainly think this […] list of [characteristics] […] highlights, generally, how narrow the research community's focus has become.*” In this paper, we therefore supplemented elicited challenges and characteristics of ED processes with challenges and factors from language engineering, derived from personal experience of process modelling in various domains. All suggested challenges for an ED process modelling approach are used for comparison purposes of engineering design, software engineering and business administration and are listed in Table 4. Based on the similarities and differences between the domains we may be able to reuse insights and techniques from other areas in engineering design, including tools. Similarly, using the challenges and characteristics proposed in this paper could be taken as the beginning of a systematic requirements elicitation process leading to a comprehensive specification of an ideal ED process modelling tool. Practitioners in industry may use the findings in this paper to compare existing process modelling approaches and decide on the most adequate one for their given purpose.

7. CONTRIBUTIONS AND FUTURE DIRECTIONS

Modelling engineering design processes or a fraction within the overall network of tasks is important. In order to derive requirements of ideal process modelling notations and tools, this work contributes to engineering industry and research with a set of characteristics of engineering design processes that provide the basis for such further developments.

Many authors have proposed that Product Development (PD) processes – Engineering Design (ED) processes as we termed it in this paper to differentiate between engineering design and software development – can be improved through modelling. Development and/or choice of adequate process modelling notations and tools necessitates understanding of engineering design process characteristics. Reviewing the literature and drawing on responses from our survey among process modelling experts in the engineering design research community and in industry, this paper has suggested that engineering design processes are described by three categories of challenges with three sub-categories, namely *development*, *collaboration,* and *products and services*. Each category comprises a set of characteristics of engineering design processes. With respect to the first challenge, *development*, engineering design processes are complex, iterative, and ill-defined. With respect to the second challenge, *collaboration*, engineering design processes are embedded in an ecosystem of processes with multiple interdependencies and interactions between different processes, people involved, and processes and organisations. With respect to the third challenge, *products and services*, engineering design processes are constrained and influenced by the physical nature of the artifact developed, economic and market constraints, and legislative and regulatory constraints. In order to derive requirements for process modelling notations (and tools), this paper further suggested consideration of a complementary set of three categories of challenges with their respective sub-categories which are derived and based on language engineering: *tool support*, *formality*, and *pragmatics/flexibility*. The fourth challenge, *tool support*, is sub-divided into automatable sub-activities, conceptual clarity, and formal semantics. The fifth challenge, *pragmatics*, lists supportive eco-system, practical tools, and adequate concrete syntax. The sixth challenge, *flexibility*, proposes scalability, customisability, and ensured evolution as characteristics. The paper has further compared these elicited and suggested challenges and characteristics within the domains of engineering design, software engineering, and business administration. This approach provided a first step in a requirement elicitation process for an ideal engineering design process modelling notation.

In further work, we will, firstly, complement written responses from the questionnaire with answers through in-depth interviews. Secondly, we will apply our approach to other domains with extensive reliance on process modelling, such as transport. Thirdly, results included in this paper need to be compared to the results of formal design process definitions and tested in the context of a real design problem. Lastly, we will use the elicited set of characteristics of engineering design processes presented here to derive requirements for an ideal Product Development (PD) process modelling notation (and toolset).

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