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Core information categories for engineering design – Contrasting empirical studies with a review of integrated models

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Abstract: The delivery of products and services or capabilities over long product life cycles requires extended support of engineering and management tasks by knowledge and information management. Integrated models which capture information about product, process and rationale have been developed and proposed in the literature to support the different product life cycle phases as well as the reuse of components, modification and update of products. Information needs which have been identified in previous engineering studies are contrasted with the elements from integrated models. A systematic literature search identified models which are briefly described and their elements are contrasted with a schema of information needs derived from engineering research. The analysis identifies a lack of consensus (at basic syntactic and semantic levels) among the models and significant disparities in their coverage of the needs. Detailed examination of the models also reveals varied granularity in terms of number of model elements utilised to describe specific needs. Based on the findings, information categories are classified into a core set for future integrated models and additional candidate and related information needs. The benefits beyond modelling are also discussed.

Keywords: Knowledge and Information Management, Information requirements, Modelling, Product Model, Process Model, Rationale, Integrated Model

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1. Introduction

Capturing information and knowledge in engineering work is not a new endeavour. Historically, designers were encouraged to use and retain their personal logbooks during their apprenticeships. Experienced designers thus possessed a wide range of successful design solutions. The classifications of standard components in the 1950s and 1960s were developed in order to encourage reuse long before computer-based systems were available (Sivaloganathan, Shahin 1999).

Increasing division and specialisation of work, especially design work, makes it more difficult for an individual design engineer, project manager or even the project team to understand each piece of information produced during the design process. Products and services are routinely engineered and delivered by global networks of companies. The scope of information flows and exchanges in the product service business goes far beyond the boundaries of a single company (Ball et al. 2006).

Capturing knowledge and information for business purposes should be driven by re-use requirements as a high part of design work is reuse and fitting of known solutions to new conditions (Andreasen 1992a, Markus 2001). Before a design engineer or a design team is willing to reuse a previous design solution, they must understand the previous design's underlying rationale (Moran, Carroll 1996, Regli et al. 2011). Properly understanding the design requires design background information (Kimura, Suzuki 1995).

An integrated model is understood in this paper as one that combines representations of product, process and rationale. Such models facilitate understanding by answering questions related to the what, why and how a design was made (Kimura, Suzuki 1995, Demian, Fruchter 2006, Baxter et al. 2007, Zdrahal et al. 2007). We limit our approach to integrated models because models restricted to a single domain (i.e. purely product, process, or rationale) are by definition constrained in their ability to satisfy information needs owing to their singular focus. These requirements about what, why and how were also expressed in an empirical study by a Service Engineer from the Aerospace industry as follows: '*The drawings are always there along with details, but a lot of "detective work" is often involved when realising why features are there/material choices for example and hence how they can be improved'* (Heisig et al. 2010). Furthermore this quote points to the hidden costs of '*a lot of detective work'* if these requirements are not met.

Engineering research has mainly addressed this requirement by developing methods and applications to support the capturing of the relevant information and knowledge such as design histories (Ullman 1991, Qureshi et al. 1997) or design reuse systems (Baxter et al. 2007). Furthermore the need for electronic exchange of engineering data has driven the development of integrated models (Levy et al. 1993, Brissaud et al, 2003, Sudarsan et al, 2005, Zdrahal et al. 2007).

The aim of this paper is to identify the core information categories required to satisfy industry information needs and whether existing models possess these elements. The remainder of this paper addresses this aim as follows: The research methodology to identify integrated models is described (Section 2). The information needs in engineering work derived from empirical studies and laboratory research undertaken in engineering design are established (Section 3). The identified models from the engineering literature are described (Section 4) and compared against each other (Section 5). The comparison of the models with the information needs from engineering work is presented and the core information categories are proposed (Section 6). The paper ends with a discussion of the findings and limitations of the work (section 7) and the final conclusions and opportunities for future work (Section 8).

2. Research approach

In order to identify core information categories (or synonymously, core information elements), we need to establish the information requirements for engineering design work. For this first task we will revisit the results from previous empirical and laboratory studies undertaken by engineering design researchers focusing on the information needs of managers and engineers along the product life cycle.

For the assessment of the coverage of these needs by engineering models, we need to identify integrated models which aim to support the capture of knowledge and information throughout the whole product life cycle. Our assumption is that the elements mentioned in these models should represent or match the information categories needed by engineers and managers for their tasks. For this task, we carried out a systematic search and review of journal and conference papers following the methodology outlined by Tranfield et al. (2003) to ensure that a methodological, transparent, and replicable review of the literature was undertaken.

Before we match the articulated information needs with the models from the literature, we want to compare the model contents and elements to each other in order to establish the commonalities and differences among the models. This extends the work undertaken by others focusing on the understanding of “function” only (Chandrasekaran, Josephson 2000; Vermaas, 2011). This is equivalent to our comparison of the empirical studies, but will be more detailed due to the availability of explicit element definitions. This will yield an understanding whether models share a common language when they are supposedly covering the same need.

We generated a list of 30 keywords (see Annex Table 1) to start the literature search to identify integrated models. We also consulted with colleagues from the field in different countries to access literature (e.g. PhD dissertations) which might provide more detailed information than conference or journal papers but which would not be referenced in engineering databases. In order to ensure transparency a review protocol was kept to document the process and all relevant decisions.

The selected keywords (Annex Table 1) were then constructed into a set of 40 search strings (Annex Table 2), which were used to conduct searches in electronic databases INSPEC and Compendex (Annex Table 3). For the purpose of this study, we included journal and conference papers published in English, German, French and Spanish language. No time limit (1884-2012) was applied to the searches.

The results from the single search strings were narrowed further if the number of hits returned exceeded more than 1000 papers. In these cases different strategies were applied to narrow down the number of returned papers. We eliminated the duplicates from the list of papers using the functionality of the Engineering Village platform. Another strategy used was to employ the following keywords from the controlled vocabulary 'Product Design', 'Product Development', 'Computer Aided Design', 'Design', 'Life Cycle', 'Computer Aided Engineering', 'CAD', 'Standards', 'Database Systems' to narrow down the papers returned from the database until about 500 hits. A third strategy applied was to add one additional key word from the list of keywords (see Annex Table 1) to narrow down the search results. If the number of returned papers was below 500 hits, we checked title and abstract of the paper in order to make a first pass decision if the paper was relevant for our research task.

The final list of papers was downloaded to EndNote from each search string (Annex Table 2). EndNote filtered out the duplicates from each single search. Some papers were duplicates as different surnames were used in the two databases searched. We also excluded those papers which were conference papers and later published as journal papers with the same title. In such cases we opted to include the journal paper for further consideration.

A total of 2318 papers were identified from the electronic databases INSPEC and COMPENDEX between June 2012 and August 2012. From reviewing title and abstract a total of 432 papers were downloaded to EndNote. After excluding the duplicates from each search, 239 papers remained. Six papers were manually eliminated as they were published by the same person but different second names were used in the databases.

From these 233 papers a further 43 papers were excluded which described software developments or software tools without underlying models. Also papers addressing the construction industry and civil engineering were excluded. For the remaining 190 papers the full papers were retrieved from online journals or conference proceedings or the authors were directly contacted.

The Endnote data and the full papers were shared with the second author who conducted another review of the dataset in order to identify and validate the previous selection of those papers which provided enough detailed information about product, process and rationale models. This independent review resulted in papers which provided sufficient detailed information about the model to be included into the further analysis (see Table 1). This final set of papers were classified in three categories (a) relevant papers including detailed model information with an explicit definition of their model elements (e.g. NIST-CPM (2005): Definition of Function: "*What the artefact is supposed to do*.", Chromosome (1990/92/97): Function: "*Defined as the ability of the system to create a physical effect*."), (b) papers addressing the research topic but providing less information, e.g. only element names without their definitions, and (c) a third set of papers which provided insufficient or no information about models that would be useful to answer our research question.

Table 1: Models included into the review and main papers

Name	Papers
Models **with** definitions of model elements available from the literature	
Chromosome Model	Ferreirinha et al. (1990), Andreasen (1992a), Malmqvist (1995, 1997), Malmqvist, Schachinger (1997)
Product and Process Model (PPM)	Harani 1997
Methodology and software tools Oriented to Knowledge based engineering Applications MOKA	MOKA 2000, Stokes 2001, Arndt, Klein 2002, Brimble, Sellini (2000)
Integration of Product – Process – Organisation for engineering Performance	Girard, Castaing, Noel 2002, Bettaieb 2005, Girard, Robin 2006, Girard et al. 2003, Robin, et

Name	Papers
improvement IPPOP	al. 2005, 2007, Rose et. 2007, Yesilbas et al. 2006
Product/Process/Resource/External Effect FBS-PPRE	LaBrousse 2004, Bernard, Perry 2003, Bernard, et al. 2006
Core Product Model (CPM), Open Assembly Model (OAM), DAIM	Sudarsan et al. 2005, Fenves et al. 2008
Collaborative Model for capturing and representing the engineering design process CoMoDe	Gonnet, Henning, Leone 2007, Gonnet 2003
Prozess + Produkt + Konfiguration Pro2Kon	Abramovici, Chasiotis 2002, Chasiotis 2006
Product Life Cycle Support (PLCS) Concept Model	Pratt 2005, Eurostep 2010, http://www.plcs.org, ISO 10303-239
Models **without** definitions of their model elements (classes)	
Diagrammatic model	Grebici et al. 2009
Engineering design knowledge	Baxter, Gao 2006, Baxter et al. 2007
Integration Core Model	Shah et al. 1996; Qureshi et al. 1997; Shah et al.2000
Integrated product, process and rationale model	McKay et al. 2001, 2009
Hierarchical model for design rationale	Nomaguchi, Y., Ohnuma, A., Fujita, K. (2004)
Information model for product and process	Taura, T., Kubota, A., (1999)
History Knowledge Management	Zhong et al. 2006

For the comparison, we extracted the labels and definitions of all model elements disclosed in the literature from both sets of models into an excel spreadsheet. The two first authors performed independently two classification steps to match the elements with the needs. In the first step, the element name/label was matched with the category label. The remaining model elements were matched to the keywords of the need categories in the second step. After both authors performed these matching exercises, both met to compare their individual results, discussed differences and agreed a final comparative list. The final list was used to identify those areas which were best covered by existing models and the gaps. We computed the ‘coverage’ (Wyatt et al. 2009, Grebici et al. 2009) as a measure between a model and the information categories from empirical research in order to assess how well the models satisfied the industry requirements. Finally we computed for each category of information requirements the product of the number of appearances across the models with the frequency in empirical studies. The result showed the most mentioned elements in integrated models and empirical studies, which we propose as a core set of categories to be considered in future integrated modelling.

3. Information requirements from empirical research

The information needs of engineers and managers in engineering work have been investigated from very different perspectives. Early empirical research was based on laboratory experiments with mechanical engineering students using protocol analysis (Kuffner, Ullman, 1991) to identify the information and knowledge required to undertake typical engineering tasks. Gruber and Russel (1992) analysed eight case studies and systematised the needs into generic questions representing information needs of engineers. Observational methods using discourse analysis have been used to understand information needs of engineers in aerospace industry (Marsh, 1997) and in particular the differences between novice and experienced design engineers (Ahmed, Wallace, 2004). Rodgers, Clarkson (1998) used semi-structured interviews with designers working in small and medium-sized firms (8 firms with seven to 250 employees) from different sectors to identify first and second order knowledge needs.

As business models evolved, placing more emphasis on maintenance, service and the whole product life cycle, studies focused on the information requirements of service engineers and the feedback from service to design based on semi-structured interviews (e.g. Jagtap, et al. 2007).

Survey methods about information needs have been rarely applied in engineering design research with the exception of Court (1995, n=211) Heisig et al. (2010, n=137) focusing on engineers from manufacturing and service industries in the United Kingdom.

In order to establish the information requirements of engineers and managers throughout the product life cycle, we use the results from the most recent empirical study (Heisig et al. 2010) and compare those needs identified by previous research (Kuffner, Ullman, 1991; Gruber, Russel 1992; Court 1995; Baya 1996; Marsh, 1997; Rodgers, Clarkson 1998; Jagtap, et al. 2007). Table 2 lists the total of 69 categories according to the frequency of each category in those eight empirical studies. ‘Component/Part’, ‘Requirements’ and ‘Test’ are the most common categories appearing in seven out of eight studies.

For the purpose of this research, a category represents an information need as articulated by engineers in previous research. We adopted the categories identified by Heisig et al. (2010), who used a bottom-up classification approach, following a qualitative research methodology (Bradley et al. 2007; Miles, Huberman 1994; Pope, Ziebland, Mays 2000). Their process involved three researchers who independently categorised the free-text responses with two iterations to achieve a consensus among all three coders. The inter-coder realiability reported was 85.6%, which is above the recommended threshold of 80% (Miles, Huberman 1994).

The adoption of the categorization identified by Heisig et al. (2010) has its limitation in regards of the types of categories. For example, “Function” and “Design documentation” seen from a conceptual perspective represent different types as one refers to the actual content while the other could be classified as information carrier or information source. While such mixing of types (content, carriers, source) is not ideal, it reflects the reality of how the respondents expressed their information needs. Another limitation is due to the lack of disclosure of definitions of the categories identified by empirical studies, where typically only the category names are listed, with the illustrative examples of (Heisig et al. 2010) and the questions list (Jagtap, et al. 2007) being helpful exceptions to this norm. Still, we believe that mapping the information needs from different empirical studies with the models entities proposed by design research is a necessary task to advance a step towards agreement and guidance about what information should be captured and shared via electronic means or between human actors in engineering. This agreement does not imply the adoption of a unified understanding. Vermass (2011) analysed the different meanings of function and sees advantages in this ambiguity of core concepts in engineering. Further conceptual discussion would be a useful endeavour given the research undertaken in the field of information sciences (Allen, 1969; Lin, Garvey, 1972; Derr, 1983; Dervin, Nilan, 1986; Hewins, 1990; Naumer, Fisher, 2010) evolving from a physical object paradigm of information exchange towards a social understanding incorporating human actors and the social-cultural context shaping information needs. Fidel (2012) reviewed the discussion about the definitional challenges of the concept 'information need' and suggested the notion of "*elements in context*" instead.

This list of information needs was presented and discussed with representatives from aerospace industry, engineering and software as well as other engineering design researchers during the research project. Industry representatives did not raise any objections regarding the categories of information needs identified. Academic partners suggested to further narrow down the list and to work with a less extensive list of categories. This prompted the process of contrasting the "long list" with categories proposed in the models presented in this paper.

Table 2: Information needs categories from empirical studies

	Categories of information needs	Kuffner, Ullman, 1991	Gruber, Russel, 1992	Court et al. 1993, Culley, McMahon 2005	Baya, 1996	Marsh, 1997	Rodgers, Clarkson, 1998	Jagtap et al. 2007	Heisig et al. 2010	**Total**
1.	Component/ Part	1	1	1	1	1		1	1	7
2.	Requirements		1	1	1	1	1	1	1	7
3.	Test		1	1	1	1	1	1	1	7
4.	Parameter		1	1	1	1	1	1	1	7
5.	Maintenance info		1	1		1	1	1	1	6
6.	Constraints		1		1	1	1	1	1	6
7.	Feedback & Suggestions		1	1		1		1	1	5
8.	Material	1	1	1		1		1	1	6
9.	Performance	1		1	1		1	1	1	6
10.	Rationale	1	1		1	1		1	1	6
11.	Service		1	1			1	1	1	5
12.	Standards		1	1		1	1	1	1	6
13.	Behaviour	1	1		1			1	1	5
14.	Calculations/ Analysis		1	1	1			1	1	5
15.	Design Process		1		1	1	1		1	5
16.	Design Documentation		1	1		1	1		1	5
17.	Functions	1	1		1			1	1	5
18.	Functional relationships	1	1		1			1	1	5
19.	Geometry	1	1		1	1			1	5
20.	Manufacturing info	1		1		1	1		1	5
21.	Options & Choices		1		1	1		1	1	5
22.	Specification	1	1		1			1	1	5
23.	Reliability		1	1			1	1	1	5
24.	Assumptions		1		1	1			1	4
25.	Changes/ Modifications	1	1					1	1	4
26.	Costs			1			1	1	1	4
27.	Design description	1	1			1			1	4
28.	Difficulties, Problems, Issues		1			1		1	1	4
29.	Features	1	1		1				1	4
30.	Legislation			1			1	1	1	4
31.	Method		1	1		1			1	4
32.	Plans				1	1		1	1	4
33.	Product	1				1		1	1	4
34.	Report, Records (non-design)		1	1				1	1	4
35.	Criteria		1					1	1	3
36.	Decision		1		1				1	3
37.	Design for Reuse			1				1	1	3
38.	Design Solutions		1		1				1	3
39.	Drawing		1					1	1	3
40.	End-User Support					1		1	1	3
41.	Marketing			1			1		1	3
42.	Peers & competitors			1			1		1	3
43.	People		1			1			1	3
44.	Product Life End			1				1	1	3
45.	Resources					1		1	1	3
46.	Safety & Risks			1			1		1	3
47.	Terminology, Glossary, Definition		1			1			1	3
48.	Achievements							1	1	2

49.	‘as-delivered’					1		1	2
50.	Correspondence				1			1	2
51.	Design reviews	1						1	2
52.	Failures						1	1	2
53.	Input data		1					1	2
54.	Learning’s				1			1	2
55.	Model(s)	1						1	2
56.	Orga. Processes & Structures					1		1	2
57.	Patent					1		1	2
58.	Projects				1			1	2
59.	Supply chain				1			1	2
60.	Timeline					1		1	2
61.	‘as-built’ info							1	1
62.	Best Practice							1	1
63.	Meeting Minutes							1	1
64.	References							1	1
65.	Sales							1	1
66.	Software							1	1
67.	Stakeholders							1	1
68.	Technologies							1	1
69.	Technical Publication							1	1

4. Review of integrated models

In this section we will describe and review existing integrated models. Table 3 provides a comparison of the principal models examined, according to their (a) aims, (b) objectives, (c) the approaches behind the definition of the models and (d) the product lifecycle scope. The aims will reveal each model’s intent in terms of information capture, reuse, representation (for communication), understanding, learning or management, etc. The objectives highlight the specific achievements or goals proposed by a given approach (e.g. retrieve the process knowledge, manage the conflict, etc.). This indicates the particular applications derived from the model. The approach taken by each model reveals the motivations, the model hypothesis and the conditions under which the information model is proposed. The lifecycle scope highlights where in the product lifecycle process the knowledge/information is captured (e.g. capture knowledge and information from calculation and simulation tasks). In addition, there is a brief descriptive summary, highlighting salient features and some of their model elements, with further details provided in the Annexes. Names of classes are capitalised.

The intended views, viewpoints, aspects, etc., are indicated in *italics* to distinguish them from explicitly represented elements.

Table 3: Comparison of models with definitions of model elements

Chromosome model	Aim	Theoretical framework for product modelling
	Objectives	Represent all the information generated during a design process in order to simplify the reuse and redesign of previous design solutions (Malmqvist, Schachinger 1997); Incorporate the design history information (e.g. rationale, alternative designs, decisions) (Malmqvist 1997); Create an information model for mechatronic products (Hallin et al. 2003)
	Approach	Based on the theory of technical system (Hubka, Eder 1988) and the theory of domains (Andreasen 1980, 1992b). Extension using function-means trees
	Scope	Parts manufacturing, assembly, use, service, destruction, and re-use
Product and Process Model	Aim	Capturing knowledge related to the product design for reuse
	Objectives	Provide a means for capturing product knowledge as the design project progresses and for retrieving the product description histories for reuse.
	Approach	Multi-model approach based on FBS (function, behaviour and structure) "Viewpoints" (Gero 1990).
	Scope	Conceptual design to the calculation and simulation tasks within the detailed design
MOKA	Aim	Capture, representation, and maintenance of knowledge associated with the engineering lifecycle for re-use
	Objectives	Analysing/modelling the engineering information/knowledge throughout the product lifecycle; Recording the knowledge models in various stages of completeness; Standardizing the storage and the structure of the knowledge units; Linking these units to maintain the original design "story".
	Approach	Based on a KBE approach suitable for describable and explicit knowledge from multiple sources
	Scope	Conceptual design, embodiment design, detailed design (including calculation and testing tasks), manufacturing and assembly
IPPOP	Aim	Facilitating design context understanding, capitalizing knowledge about interaction situations (e.g. shared knowledge) and managing the design system performance
	Objectives	Monitoring and managing the performance of the process, the product (component) and the organisation; Formalizing collaboration between actors to solve conflict situations; Providing full data traceability support for documentation and revisiting purposes
	Approach	Based upon the FBS approach and the functional product model developed in (Constant 1996), the product view representation provides basic and stable concepts (for communication between actors) with dynamic evolution
	Scope	Whole Product Lifecycle
FBS-PPRE	Aim	Capitalization and re-use of generic knowledge to shorten redesign and manufacturing timescales
	Objectives	Capturing and reusing the enterprise object; Capturing the design process history and alternatives, Managing the evolution of enterprise objects; Automating the re-design process; Evaluating enterprise performance
	Approach	An Enterprise Integration approach to modelling and managing the lifecycle of enterprise objects, extending the FBS views with more generic paradigms for products as well as processes and resources.

	Scope	Basic design, the detailed design (including simulation and calculation tasks), and the manufacturing phases
NIST	Aim	Capture product information that can be accessed, stored, and reused throughout all phases of a product's life
	Objectives	Provide unified and standard product structures; Address the semantic interoperability of next generation CAx (CAD, CAE and CAM) systems
	Approach	Based on traditional engineering design, functional reasoning and product modelling approaches (Kusiak et al. 1991) (Hubka, Eder 1995).
	Scope	Lifecycle from conceptual design to product disposal
Pro_2Kon	Aim	Improve the digital product development process by capturing explicit and implicit knowledge about the product, the design process, and its IT systems.
	Objectives	Capture of relevant knowledge about product, process and configuration
	Approach	Object-oriented knowledge management system (KMS)
	Scope	Product design (CAD), calculation / simulation (CAE) and testing
CoMoDe	Aim	Represent essential knowledge associated with design processes and their products for reuse and learning purposes
	Objectives	Provide procedures for conflict detection and resolution; Represent, capture and trace the design process history that creates the artefacts (and their models); Ensure consistency, navigability, and traceability among those models.
	Approach	An integrated deductive object-oriented model providing ontological support for the development of a Conflict Management Process tool. Relies on a procedural or operation-centred design methodology that considers the design process as procedures performing operations on an object to transform it into one having the desired attributes (Boyle 1989)
	Scope	Engineering design process

4.1 Chromosome Model

The chromosome model (Ferreirinha et al 1990, Andreasen 1992a) models products from four hierarchical viewpoints: (1) the *transformation process* in space and time of objects (material, energy, signals), (2) the *function structure* describing the functional layout, (3) the *organ* or the technical principles and (4) the *component view* (the physical embodiment of the parts forming the product). The chromosome expands this approach by adding "genetic" information that captures the origin of the design characteristics, hence the "chromosome" (Ferreirinha et al 1990, Andreasen 1992a).

Malmqvist (1997) extended the approach by using function-means trees to represent the design process, capturing design history information, e.g. design alternatives, design decisions, and their rationale. The goal was to make explanations available on how and why certain design decisions were made; to facilitate verification that a product meets its specifications; to predict the effects of design changes and the reuse of old design solutions (Malmqvist 1997). Another implementation extended the modeling scope towards the integration of information related to the design specification (Malmqvist, Schachinger 1997), including *customer needs, requirements*, and *objectives*.

4.2. Product and Process Model

Harani's (1997) integrated model emphasises the *product view*, and assumes that a product is defined by first its *functions*, then by its corresponding *behaviour* (that satisfies these functions) and finally by its *structures* (that satisfy the behaviours). It proposes a "Parameter" view to represent any quantitative or qualitative elements, extracted from the specifications or generated or computed during the embodiment and the detailed design. Parameters are related to the product structure, the function or the behaviour "Viewpoint". The behaviour viewpoint is the most developed. To represent the transformation from the behaviour to the structure, a "Product" node might encompass a function/structure "Viewpoint" with a discrete behaviour component ("BehaviourEquation" and "BehaviourVariable") and eventually their controlling "Parameters". The process model represents the product description stream, considering information about the "State" of the "Task", the "Product" and the assigned "Resources"., and representing *process behaviour*, in terms of "SequencingOperators" and "Transitions".

4.3. MOKA

The MOKA EU 25418 methodology (Stokes 2001) is a knowledge-based engineering framework, and was extended by Arndt, Klein (2002) to add 'design rationale' including 'Problem', 'Decision', 'Criteria', 'Alternative' and 'Argument' elements.

MOKA proposes a method to record raw knowledge and informal knowledge models, e.g. in semi-structured ICARE (“Illustrations”, “Constraints”, “Activities”, “Rules” and “Entities”) forms, and to transfer these to the formal level as meta-model concepts.

The MOKA Formal Model has two key models: the *Product Model* and the *Design Process* Model. The DEKLARE methodology (Design Knowledge Acquisition and Redesign Environment) enables the representation of the product family and the design process (Fothergill et al. 1995). The methodology provides product (meta-) models describing the product itself- physical components (“Assemblies” and “Parts”), the “Material” used, the intended product behaviour (“Behaviour”) and the “Functions” that it will fulfil- and how it is manufactured (“ManufacturingProcess”), its shape, size and the associated “Constraints”. Product model content includes engineering-specific aspects such as technical solutions and their principles, geometry and FEM. MOKA considers the process as the place for creating a library of general reusable patterns for problem-solving methods. The design process is seen as high level bundles of tasks for process management where the main knowledge elements are: “Goals”, “Tasks”, “Dynamic knowledge categories” (including the “Requirements” and “DesignDescription”) and “StrategicKnowledge”. Lower-level tasks may potentially be automated and have “Activities”, their “Aims”, “Rationale”, “Methods” or “Rules” and “Constraints”.

4.4. IPPOP

IPPOP (Girard et al. 2002; Bettaieb 2005; Robin, Girard 2006, 2007) builds upon methodologies by (Badke-Schaub et al 1990), (Roseman, Gero 1998) and (Eder 2004) and is based on the assumption that interaction among the techno-physical, the socio-cultural, economical, organizational and human factors influences the design system performance. Thus the integrated model should represent such interactions based on the knowledge about the *product*, the *process*, the *organisational* model and their relationships (Robin, Girard 2006).

IPPOP uses abstract classes and sub-classes to describe the product according to multiple views, e.g. "ProductData" and "ModelledEntity". *Common*, *alternative* and *view* are sub-classes of "Function", "Interface" and "Component" (structure), so a function is expressed differently between the actors and according to the context. The product's evolution throughout its lifecycle and its multiple states are represented by the "DynamicClassEntity" (allowing creation of new product entities) and "Maturity" (allowing characterisation of a product data state of evolution). "AttributeType" and "CoreType" deal with the multiple levels of the product details throughout the lifecycle.

The design process relates the organisation and product, defined as "Objectives", "Constraints" and "Resources". In the process model, classes such as "Activity" and its "Input/Output" association to the "ProductData" support traceability. Conflict resolution is represented in a "CollaborativeActivity" decomposed into "Iterations" comprising "VoteRequest" and "VoteIteration" classes. "Justifications" are associated with each "CollaborativeActivity". Sequencing "Milestones" and "Transition"), planning of activities ("Trigger" and "Constraints"), and process performance monitoring are supported.

The organisation model represents the objects handled by the actors during the collaborative process. Inspired by the approach of GRAI R&D (Chen et al. 1997), it has two basic objects: "DecisionCentre" and "DesignCentre" associated with the decision makers and the designers. Decisions have three typical "Levels", corresponding to different management levels (strategic, tactical and operational). For performance evaluation purposes, “PerformanceIndicators” are represented via the “ExpectedBehaviour” and “StructureBehaviour” classes.

4.5. FBS-PPRE

FBS-PPRE (LaBrousse 2004) is an enterprise integration approach, based upon the Function, Behaviour, Structure views. Enterprise performance evaluation is achieved by extending “Function” to the “Process”, “Product” and “Resource”, e.g. to evaluate the *pertinence of a resource,* the resource function (e.g. machine’s function) and the process function or objectives (e.g. manufacturing process objectives) must be compared. Behaviours encompass the set of rules, “BehaviouralLaws” (e.g. material properties) and a sequence of changes of “States”, with structures evolving under certain “Triggers” (stimulation).

The structure decomposes a complex system into its components, with elements composing the modelled objects and their attributes. “Features” correspond to the aspects of the product (e.g. shape) and other attributes that allow the design, manufacture, or performance evaluation of the product. ”Representations” support the state of an object throughout its lifecycle (e.g. FEM, CAD models, etc.) and describe manufacturing instructions, norms, etc.

Design process is the *process pattern* view describing how the transformations from the functions to the behaviour and from the behaviour to the structure are realised. It is viewed as contextualising the object behaviours, including environmental effects on the “system” through the modelling of the “ExternalEffect”. By “system”, FBS-PPRE denotes the set of the objects “Process”, “Product” and “Resource”.

4.6. NIST Core Product Model

The NIST information modelling framework seeks to seamlessly integrate and make available all the information produced throughout the product life cycle to everyone in an organization, along with key suppliers and customers (Sudarsan et al. 2005). It proposes an exchange protocol including four models (CPM: Core Product Model, OAM: Open Assembly Model, DIAM: Design Analysis Integration Model and PFEM: Product Family Evolution Model).

The CPM is the framework's core model, supporting information commonly shared in engineering contexts, including "Specification", "Function", "Form", "Geometry", "Material" and "Behaviour", and models associated with analysis-driven design including the "FunctionalModels" (e.g. "FEM", "KinematicModel" and "GeometricModel", such as behaviour analysis, validation and verification). It is intended as a generic, open, extensible, non-proprietary and context-independent architecture, It contains conceptual entities including "CoreEntity" (in terms of "Artefact" and "Features" instead of motors, pumps, etc.) and "CoreProperty" (including "Form", "Geometry", "Material" and "Function"). The framework intends to overcome PLM system shortcomings, including the capture and management of non-geometrical information with the class "Function" supporting functional reasoning if information on the artefact's form is absent. NIST includes "DesignRationale" to track the reasons for product information changes and the justifications for the decisions made.

"Behaviour" is considered as a "CommonCoreObject", beyond the property of an artefact (other than the traditional behavioural models, e.g. FEA, computational fluid dynamics, etc.) and includes behaviour information captured during manufacture, installation, operation and disposal, such as: cost, manufacturability, durability, etc.

4.7. Pro₂Kon Data model

Pro2Kon by Chasiotis (2006, Abramovici, M., Chasiotis, C. 2002) has been implemented as a prototype knowledge management system. The object-oriented Pro2Kon data model distinguishes four main categories: (1) *process knowledge* including process model with subclasses "DesignProcess", "CalculationProcess", "ProoftestingProcess" and related steps and methods, as well as "ExternalProcess"; (2) *design-oriented product knowledge* with "Product" and "Components" for the product structure and the "Gestalt Model" to capture the component's iterations; (3) *behaviour-oriented product knowledge* with "ProoftestingModel" and "Results", "CalculationInput", "CalculationModel" and "ResultModel"; and (4) *configuration knowledge* with "CaxSystem", "Configuration", "Parameter", "StandardParameter", "ProjectRelatedParameter" and "IndividualParameter". *Rationale* is not a distinct class, but attributes capture aspects of rationale, e.g. annotations in textboxes. Assumptions for improvements are similarly captured.

The Pro2Kon-Tool prototype supports annotation of the calculation methods, models and result models, automatic capture of class attributes and elicits information from engineers by asking for comments on improvement actions. The knowledge visualisation features allow navigation throughout the part's development history by displaying the time scale and the related versions of the models used. Links are captured automatically and the URL is stored in the tool.

4.8. CoMoDe

The Collaborative Model (CoMoDe) (Gonnet et al. 2007, Gonnet 2003) views design as an iterative process operating under a generate–test–analyze–advise–modify paradigm, with generated artefacts checked against design objectives

The authors (Gonnet et al. 2007) (Mandow, Pérez-la-Cruz 2004) consider performed design activities as evolving from the initial design specifications to the final engineering design; while identifying the design decisions associated with each activity, their context (who and when) along with their corresponding assumptions, simplifications, and underlying rationale. Five views are represented in CoMoDe: *process representation, actor representation, decision representation, requirement representation* and *artefact representation*. The core *process representation* captures and retrieves the sequence of the design activities and their execution,

CoMoDe has two granularity levels. The finer execution level captures how "DesignObjects" ("Artefact" being designed or its models) are transformed along the design process. It represents the "Operations" (a sequence of *add, delete* or *modify*) applied on various "ObjectVersions" of the "DesignObjects", and how these states (snapshot "ModelVersions") are derived. The coarser granularity level is the description level of the "Activities". This includes three "ActivityTypes": *synthesis, analysis, and decision.* The activity level traces the design process history.

History relationships are incorporated between the "ModelVersions". Attributes characterise the history of the executed operations; these include temporal and documentary information, including tool employed, actor ("Individual" or "Team") and rationale. Decision representation space elements have design rationale aspects, especially the "Position" ("PosAttribute" and "PosValue") and the "Artefact" (the different design alternatives). The "Argument" is rationale elements which support or counter the "Position". The "Resolution" is solution elements upon which the "Position" constitutes an acceptance or a denial. The decision space is considered as the specification of the evolutional "Requirements" corresponding to the design goals guiding the "Activities" and against which the "Artefacts" are checked.

4.9. Models without element definitions

We identified a second set of models in the literature search, where the papers provided the model element names but not the corresponding definitions. These models are briefly described below:

Design history (Ullman 1991, Shah et al. 1996; Shah et al.2000) has been proposed to provide a step-by-step account of events and states through which a design project proceeded to produce the final design of a product. It contains data about the designed product, the design process, and the relationship between them and at various stages of the design. Its stated aim is to prevent valuable technical knowledge being lost, or not available to the right people at the right time (Shah et al. 1996, 347). Shah, Jeon (1996) also looked at the STEP product data model for the design history model and in particular into the Integrated Generic Resources model, which includes elements for Materials, Shape Tolerances, Form Features, Product Structure Configuration, Fundamentals of Product Description and Support, and Geometric and Topological Representation. They concluded "that many of the data elements required for design history can be captured via STEP entities from these parts" (p. 351). The design history data elements proposed by (Shah et al. 1996; Shah et al.2000) are included in our comparison.

Taura and Kubota (1999) aim to support the reuse of information produced in design engineering processes by building an engineering history base. An information model is proposed to provide teleological and causal explanations to enable the intended reuse of product information. The core of the information model consists of five elements: action, object, alternative, constraint and reason.

McKay et al. (2001) proposed a framework aimed at providing the information content of a product specification in order to support the linkage between requirements and product definition which can be related to design intent or rationale. McKay et al.'s (2009) approach proposes a collection of relationships to support the definition of physical products to describe a product in its life-cycle and time. They highlight the difficulty of the unintended use of products which cannot be captured beforehand as it emerges through use and does not exist at the design phase of the life-cycle. The authors propose an integrated product, process and rationale model which will be included in our comparison.

Nomaguchi et al. (2004) proposes a framework for acquiring design rationale in the conceptual design. This is a hierarchical model of design rationale distinguishing between argument level, model operation and action level. The argument level is linked to the design process representing the decision making processes and the diverse types of information such as text, drawings, and CAD models. A conceptual model of the product or product architecture model is required to confront the design rationales in order to overcome huge and diverse contents in human agents involved. The Action level represents design process by operation primitives on the product model, which is defined as a fundamental augmentation of the product architecture model.

Baxter, Gao (2006), Baxter et al. (2007) aim to provide an engineering design reuse system which adopts the design process as a central element. Based on interviews with designers and engineers, they identified their requirements around the design of components. They do not present the detailed information model used for the system. The product ontology which is the formal vocabulary defining the product objects has not been published. Based on the requirements published in Baxter, Gao 2006, Baxter et al. 2007 we extracted the model terms.

Zhong et al (2006) developed a methodology of integrated history knowledge management in concurrent engineering to capture and reuse history knowledge. The history knowledge includes process history, design intent and domain knowledge. Process history contains design tasks, decisions and project information. The design intent is the sum of information about design method, decision causation, design steps and choice of design schemes. Domain knowledge is the sum of the design principle, the design method and the design experience, which exists in professional books, and manuals as well as people's heads.

Grebici et al. 2009 examined a representative subset of 15 design methods for general design, concept and detailed design in order to identify the information needs of engineers. This analysis served as a basis to propose a modelling tool to capture information use in design. The information requirements are derived by content analysis of text fragments and similar concepts are grouped into classes from 15 methods such as Design For Six Sigma, Quality Function Deployment via House of Quality, Failure Modes and Effects Analysis, Brainstorming, Theory of Inventive Problem Solving, Functional cost analysis, and generic elements from methods to describe Design Processes, and for capturing rationale. They used this in conjunction with an analysis of a design report to propose an integrated model, which is compared later in this study.

4.10. STEP – PLCS implementation

Complementary to more academically-inspired models, we selected the Product Life Cycle Support (ISO 10303-239, PLCS) Concept Model as the most recent implementation of the STEP standard (Owen 1993, Pratt 2005), which is widely used in industry. We included the model elements from the PLCS Concept Model as a high level model of the main concepts used in ISO 10303-239 (Pratt 2005, www.plcs.org) because it has a similar granularity measured by the number of high-level elements provided by the published model and focuses on the product life cycle. The documentation provides notes and examples in addition to the model element definitions (www.plcs.org; Eurostep 2010).

PLSC, like other STEP implementations, is written in a formal data modelling language and provides a detailed information model schema. Within this schema, all of the entities, attributes and relationships are represented and can be grouped into key concept categories such as Activities, Conditions, Life Cycle Phases, Locations, Products, Properties, Resources, and States. We did not include the Integrated Resources (e.g. Part 41, 42, 45) and other Application Protocols into our comparison due to space limits.

4.11. Other Models not included

The following contributions were not included for further analysis due to the lack of more detailed information or addressing a different discipline like chemical engineering. Brandt et al. (2008) present a support system for the reuse of design knowledge through ontologies for creative and weakly structured design processes in chemical engineering. The core ontology provides top-level concepts that describe products and processes, as well as their interrelations and dependencies, independently from any particular domain or application. The elements of the ontologies have not been published. A different approach of achieving an integrated view of product, process and rationale is proposed by Giess et al (2007). Links between elements of interest within the three representations are generated with a Topic Map by unifying both distinct elements within and across representations. Horvath, Rudas (2007) introduced the concept and method of the Integrated Model Object (IMO) to establish an organized description and management of relationships amongst closely related engineering objects, but their published work focuses on the tool and not the model. Brown and co-workers proposed the INTEREST information model (Brown et al 2004), which is based on an integrated product and process life-cycle information model. It consists of ‘physical object’, ‘activity’, ‘document’, ‘property’, ‘state’ and ‘administrative schema’, but its elegant generic nature means it requires significant instantiation of elements in order to capture needs in a practical setting.

5. Analysis and comparison of models

Having described the models it is now possible to understand how the models compare to each other in terms of content and meaning of elements.

There are various ways in which models can differ (Batini et al. 1986):

- Different perspectives or viewpoints of the modellers. The same concepts are referred to by different syntactic terms or with the same syntax but in different structures.
- Common concepts represented by identical (or otherwise) syntactic terminology and different *semantic relationships* can exist. Two elements are related semantically if they are: *identical*, *equivalent*, *compatible* or *incompatible*, where: *Identical:* has same structure (or the same construct model), represents coherent specifications and the same meanings; *Equivalent:* involved in equivalent model constructs with coherent specifications and the same meaning; *Compatible:* involved in constructs which are not contradictory, with non-contradictory specifications and meanings.
- Concepts which lack semantic relationships but still are related by *semantic properties*. Here the elements share some meaning or their meanings are related (e.g. the meaning of country is related to the meaning of state by the relation “belong to”).

5.1. *Comparison of model syntax*

We identified the common concepts (attributes are not considered) across the models based on the syntactic terms used in the model classes (Table 4). In this paper, “syntax” and “syntactic” includes “lexical” terms. Over 300 different terms are used to describe the different concepts found in models with element definitions (see Annexe 2).

Table 4: Common concepts used in the models. X marks the existence of the concept in the model, and terms in parentheses denote the specific word used for the concept in the model.

Model	**Concepts used**					
Year	**Function**	**Behaviour**	**Resource**	**Process**	**Task**	**Structure**
Chromosome 1990/92/97/ 2012	**X**			**X (transfor-mation)**		**X**
PPM 1997	**X**	**X (equation)**	**X**	**X**	**X**	
MOKA 2001	**X**	**X**			**X (Activity)**	**X**
FBS-PPRE 2004	**X**	**X**	**X**	**X**		**X**
IPPOP 2004	**X**	**X**	**X**	**X (model)**	**X (Activity)**	
NIST CPM 2005	**X**	**X**				
Pro2Kon 2006				**X (model)**	**(Design Step, Calculation Step)**	**X**
CoMoDe 2007			**(Actor)**		**X**	

“Function”, “Behaviour” and “Resource” are the three most commonly used terms. We conclude that there is no explicit syntactic consensus among the terms. However, there may be concepts with different syntax but shared semantics. Likewise syntactically identical terms may have different semantics.

5.2. *Comparison of model semantics*

It is important to determine the similarities and differences of the semantics of the most common terms: “Function”, “Behaviour”, “Resource”, “Structure” and “Activity” or “Task”. This requires determining whether semantic relationships exist between the term's different definitions, and if the definitions are compatible, do they share semantic properties?

5.2.1 Function

Analysis of the model constructs reveals that "Function" elements are represented in different (but non-contradictory) ways (see Table 5), leading to different applications of the element "Function". Similar concepts define "Function" across most models. MOKA extends the definition of "Function" to the process (*identified required activity*), due to the problem-oriented definition of the tasks. FBS-PPRE has the most divergent function-related concepts, extending it to process, product and resource.

There is a subtle variation between MOKA's *potential artifact* and FBS-PPRE's *product*. In MOKA, functions can be fulfilled by either the technical solution or the principles of solutions, which encapsulate an initial idea of how the function will be satisfied. These definitions differ slightly from those in PPM and IPPOP, where the function consists of "*what the artefact does*" or "*action of the product or its components"*. For IPPOP, the difference is due to measuring the performance of the product via the performance attribute, function is associated with the product's structure (component). In PPM the function is associated with the *artifact* which is a result of the process.

Table 5: Concepts associated with the term "function" in six models

Model element "**Function**"	**Chromo-some** 1990/92/ 97/2012	**PPM** 1997	**MOKA** 2001	**IPPOP** 2002	**FBS-PPRE** 2004	**NIST-CPM** 2005
Concepts or phrases describing the **definition** of the	Defined as the ability of the system to create a physical	What the artefact does. It considered as a nature of a view-	Purpose of a potential artefact.	Action of a product or its compo-nents.	The goals, Finalities of a modelled object.	What the artefact is supposed to do.

element	effect.	point.				
Describing additional **characteristics**		Not described	- Required behaviour - Identified required activity	Not described	Process objectives User's expectances about the product Resource function, competence or performance	Artifact satisfies the engineering requirements largely through its function

Thus we conclude that *compatible* definitions of "Function" are found in Chromosome, FBS-PPRE, MOKA, and NIST models. *Compatible* definitions are also highlighted in IPPOP and in PPM's model. However there is *incompatibility* between "Function" in Chromosome, FBS-PPRE, MOKA, and NIST versus "Function" in IPPOP and PPM. The compatible definitions share some *semantic properties*, e.g. both PPM and IPPOP share the meaning of *"action"* or *"what the artefact does"*. This result confirms previous research comparing functions only (Chandrasekaran, Josephson 2000, Vermaas, 2011).

5.2.2 Resource

The "Resource" element has multiple representations of the element (see Table 6). A resource in FBS-PPRE is an attribute to the "Input/Output" class, itself associated with the "Behaviour" class, whereas in IPPOP and PPM, a resource is a class associated to a task. The resulting different applications highlight different intentions for the "Resource" category, arising from the product lifecycle scope, the objectives targeted by the considered model or the hypothesis dictated by the underlying approach.

In FBS-PPRE, *object* is used for a resource as this is considered an enterprise object for managing its lifecycle. The resource cannot be temporal. Resources are further differentiated in that a resource is *not a result* of the project but a means to *satisfy its* [the project] *objectives*. Resource is subtly different in PPM and consists of the *methodological means (methods)* necessary for the *execution* of the tasks during the calculation and simulation phases (which is this model's scope). The extra aspect of resource in IPPOP relates to the two organisational levels of granularity (strategic/project and operational/task).

Table 6: Concepts associated with the term "resource" in four models

Model element "**Resource**"	**PPM**	**IPPOP**	**FBS-PPRE**	**Pro2Kon**
Concepts or phrases describing the **definition** of the element	Is necessary for the task to be carried out.	Needed for the completion of a task or project	Is an object (material, energy, software or human) which is exploited in order to satisfy objectives	In the concrete case CAS-, CAE-, CAS- or DMU-System
Describing additional **characteristics**	Method-based	Hardware/ software, methodological, informational, human	Characterised by its nature: material, energy, software, human	

In IPPOP, the resource-related concepts (*human*, *software*, *hardware*, *informational* and *methodological*) are employed as *links* between the *organisation,* the *process* and the *product views,* e.g. the *informational* (e.g. a product attribute) and *the human resources* associated with a collaborative activity consist of links between the product, the organisation and the process. Specifying the resource's *nature* aids in understanding the target objectives and performance indicators associated with decision and design activities.

These variations mean that there is no possible equivalence among the definitions. *Compatibilities* are highlighted such as between PPM's and IPPOP's definitions, as they share a semantic property that a resource has a *method* as a type. The FBS-PPRE definition does not contradict those in PPM, MOKA ad IPPOP. It shares semantic properties with the IPPOP definition in that a resource has *human, material* and *software* types. The other aspect highlighted in FBS-PPRE and which is compatible with all of the other definitions, is that a resource *cannot be a result from a project/process but contributes to it*.

5.2.3 “Behaviour”, “Structure” and “Activity”

The model construct analysis shows that the “Behaviour”, “Structure” and “Activity” elements have different representations, leading to differing applications.

Although the diverse concepts defining “Behaviour” (Annexe 2) are not contradictory, some appear incomparable, i.e. FBS-PPRE (*“describes the dynamic of an object”*) and MOKA (“*satisfies the intended function”*). The concepts defining “Behaviour” in MOKA, NIST and IPPOP are compatible. They share a semantic property that product behaviour should be defined in combination with its function. Both MOKA and IPPOP describe “Behaviour” as a discrete series of static states of the product, whereas PPM uses a contradictory characterisation of the product behaviour as continuous values calculated by equations. In the Chromosome model, the term ‘behaviour’ is not explicitly used. According to Andreasen (2012), “both organs and use activities are realizing functions and therefore carrying ‘behaviour’. Organs are identified by their core function, their function properties and interaction with other organs”.

Concerning “Structure”, contradictory model constructs are observed in FBS-PPRE and MOKA. Structure in FBS-PPRE is intrinsic to an object (“Representation” or “PrincipleOfSolution”); the class “Structure” is represented as a part of the class “Object”. In MOKA, the “Representation”, “TechnicalSolution”, etc. are parts of the “Structure” class. This contradiction is highlighted in the definitions of “Structure” in both models (see Annexe 2). Structure in MOKA and Pro2Kon have some compatibility, sharing a semantic property that a structure is a mereological organisation (part-whole) of elements. In the Chromosome model structure is the system model's characteristic and representation. Three structures are presented: Structure of use activity, of organs and of parts. Each of these entities and their relations has specific characteristic breakdown frameworks. (Andreasen 2012)

The "Activity" or "Task" shows both compatibility and incompatibility. In IPPOP, MOKA and CoMoDe, the task is a high-level element associated with activities representing how the process advances. The lower level when it's represented consists of the operations (see CoMoDe; Gonnet et al. 2007). In PPM's, the task consists of the operational and lowest level of the process. Malmqvist (1997) proposed Function-Means-Trees to complement the Chromosome product model to incorporate the "Design Process" which is understood as "a process in which an abstract problem formulation in terms of a `need' is successively transformed into a manufacturable product description" which can be divided into phases and steps.

The comparison of the model elements shows that from a large number of terms only "Function", "Behaviour" and "Resource" have been identified as the most commonly used terms. This suggests that no explicit syntactic consensus exists among the different models. The analysis of model semantics shows that even behind the identical concepts different meanings are applied in the different models.

6. Comparison between needs and model elements

6.1. Comparison of information requirements with model elements

The results of the comparison of information requirements with the elements of the integrated models are shown in Table 7 and 8. The analysis reveals that models cover between 7% and 45% of the needs in industry with an average of 24%. The highest coverage of 45% is achieved by the diagrammatic model (Grebici et al. 2009) which covers 31 categories of information needs (Table 8). From models with element definitions, the research-led models IPPOP, MOKA and NIST are covering about a third of the needs identified in empirical studies while the industry-led STEP PLCS covers 41% (Table 7). Even if we reduce the categories of information needs excluding such needs beyond the engineering domain (e.g. "Best Practice", "End-User Support", "Marketing", "Peers & Competitors", "Sales" and "Stakeholders") the coverage per model only increases between 1% and 4%. Further exclusion of generic categories (e.g. "Correspondence", "Meeting Minutes", "Report/Records (non-design)") increased the coverage to an average of 27%/30%. Note that the "Core 22" rows refer to the coverage percentages when only the proposed core set of information categories are considered – these are described shortly (see Table 12).

Table 7: Coverage of information needs by models with element definitions

	Models **with** definitions									
	1 Chro.	2 NIST	3 MOKA	4 IPPOP	5 FBS-PPRE	6 PPM	7 CoMoDe	8 Pro2Kon	**Ø**	STEP PLCS
Total Σ	17	19	21	20	11	9	11	13	15	28
Coverage	25%	28%	30%	29%	16%	13%	16%	19%	22%	41%
Coverage (excluding Background info. n=63)	27%	30%	33%	32%	17%	14%	17%	21%	24%	44%
Excluding background and generic (n=56)	30%	34%	38%	36%	20%	16%	20%	24%	27%	45%
Core 22	64%	68%	73%	68%	36%	32%	45%	45%	54%	55%

Table 8: Coverage of information needs by models without element definitions

	Models **without** definitions							
	9 Baxter et al.	10 Grebici et al.	11 McKay et al. 2001/09	12 Nomaguchi et al.	13 Shah, et al.	14 Taura, Kubota	15 Zhong et al.	**Ø**
Total Σ	26	31	10 (7)	13	24	5	9	17
Coverage	38%	45%	14% (10%)	19%	35%	7%	13%	24%
Coverage (excluding Background info. n=63)	41%	49%	16% (8%)	21%	38%	8%	14%	27%
Excluding background and generic (n=56)	46%	55%	18% (9%)	23%	43%	9%	16%	30%
Core 22	77%	95%	41% (23%)	41%	82%	23%	23%	55%

The comparison of the model elements with the needs (Table 9) shows that elements related to the description of the **design process** has been identified in 15 out of the 16 models. The labels and the semantics used are different such as "*activity*" (MOKA, CoMoDe, IPPOP, STEP/PLCS), "*task*" (MOKA, CoMoDe, IPPOP, STEP/PLCS, Baxter, Gao 2006, Grebici et al. 2009), "*process*" (FBS-PPRE, PPM, Chromosome), "*process step*" (McKay et al. 2009) or "*sequence of steps*" (Shah Jeon 1996), "*action*" (Taura, Kubota 1999) and "*design process*" (Nomaguchi et al. 2001, Grebici et al. 2009) or "*design tasks*" (Zhong et al. 2006) but the basic information need is addressed, albeit at different levels of granularity. These different levels of granularity are approximated by the numbers in each cell in Table 9. They represent the number of elements of a model associated with an information need. Model 3 (MOKA) provides five model elements to map the "Design Process" while the Chromosome model (No.1) used one element only. About 38 model elements from 15 models address the need "Design Process" and 35 elements from 13 models map the need "Rationale".

Table 9: Categories of information needs with highest coverage across all models

Needs	Σ Models	Σ Elements	Models: with definitions 1	2	3	4	5	6	7	8	without definitions 9	10	11	12	13	14	15	STEP PLCS
1. DesignProcess	15	38	1		5	2	1	2	4	4	3	2	1	2	6	1	4	4
2. Rationale	13	35	1	4	2	1			1		1	6	7	4	5	2	1	1
3. Component./Part	12	20	1	5	2	2		1		1	2	3	1		1	1		1
Constraint	12	14	1	3	1	1	1			1	1	1	1		1	1	1	
4. Functions	11	15	2	2	1	2	1	2			1	2		1	1			1
Parameter	11	20	2	4	3			1	2	3	1	1	2		1			1
5. Product	10	13		1	1		3	1	2	1		1	2		1			6
Requirement	10	14	3	1	1	1			1		1	3	2	1				1
6. People	9	14				1			3	1	3	1	1		3		1	2
7. Geometry	8	13		2	3			1		1	1	2	2		2			x^1
Options	8	14	1		2	3			2		2			1	2	1		
8. Behaviour	7	16		1	4	2	2	2				4	1					
Calculation	7	10		1		1			1	3		3		1				1
Decision	7	10			1	3			2		1	1		1	1			
Features	7	17	1	5	2		1				1	2			5			
Material	7	9	1	3	1						1	1	1		1			x^2
Method	7	12				1				3	2	3		1			2	1
9. Design Solut.	6	11	2		2		2				2	2		1				
Difficulties	6	6			1						1	1	1	1	1			
Input data	6	7				1	2	1		1	1				1			
Manufacture	6	7		2	1	1	1					1			1			
Models	6	7	1		1					2		1		2				1
Project	6	6				1			1	2	1						1	1
Resource	6	13				5	1	1				5					1	1
10. Performance	5	9	1			1	3				1	3						
Specification	5	14	1	2								7	2		2			
Test	5	6	3							1	1	1						1
Funct. Relat.	5	6	1	2									2		1			1

Table legend: Cells show the number of model elements covering the information need. x^1 STEP 10303-42 Geometric and topological representation, x^2 STEP 10303-45 Materials (Step Resource Schema, 2013)

A total of 50 (72%) of 69 information and knowledge needs are covered by the models reviewed. Most models also satisfy the need for information about the **component/part** which was identified by the empirical study as the common design object, engineers are thinking about/around (Heisig et al. 2010). The product related categories **product** and **feature** are represented in ten and seven models respectively.

The information request regarding the **rationale** is also covered by the majority of the models analysed. The difference was found again in the level of granularity of models. While practitioners ask for "*reasons, why a design is as it is*" or "*why not selected*" (Heisig et al. 2010), models provide more structured details such as "*argument*" (CoMoDe, Shah Jeon 1996, McKay et al. 2009), "*argument supporting*", "*argument counter*" (McKay et al. 2009) or "*Pro argument*" and "*Con Argument*" (Grebici et al. 2009). In the Chromosome model the model element "*solved_by relations*" "also store[s] the rationale or reasons for choosing this particular means" (Malmqvist 1997). In the NIST models, different types of rationale are distinguished through its subclasses of "Design Rationale", "Evolution Rationale" and "Family Derivation Rationale". STEP PLCS uses "Justification" to describe "*the reasons for something*".

The following 22 (32%) information and knowledge needs are only mentioned in up to four models (frequency): "as-built" info.(2), "as-delivered" (2), Assumptions (1), Changes & Modifications (2), Cost (2), Drawing (3), Design description (4), Design documentation (3), Design Criteria (2), Design-Reviews (1), Failures (1), Feedback & Suggestions (2), Legislation (2), Organizational Processes & Structures (4), Plans (1), Product life end (cycle) (4), Safety & risks (1), Service (2), Software (1), Supply chain (1), Technology (4), and Timeline (4).

Just under a third (19) of information and knowledge needs articulated by engineers and managers in engineering functions in industry are not addressed by any of the models reviewed: Achievements, Best Practice, Correspondence, End-User support, Learning's, Maintenance Information, Marketing, Meeting minutes, Patent, Peers &

Competitors, References, Reliability, Reports/Records (non-design), Sales, Similar Design for Reuse, Stakeholders, Standards, Terminology/ Glossary/Definitions and Technical publications.

The comparison shows that information needs which are outside the core engineering design areas, such as 'End-User support', 'Marketing' and 'Sales' and generic categories like 'Correspondence', 'Meeting minutes', 'Stakeholders' and 'Technology, Glossary, Definitions', are not addressed by the models reviewed. This is similar to the differentiation introduced by Kimura, Suzuki (1995), who distinguish between the design background and foreground information. The background information is used for generating product definition but is not explicitly represented in the product description. Under the category design background information Kimura, Suzuka lists the following items: 'requirements', 'specifications', 'assumptions', 'constraints', 'design history', 'design intents', 'design standards', 'trial-and-error processes', 'design methods', 'design modification records', 'standard parts', 'engineering analysis', 'manufacturing process/resource information', 'rationale'. Foreground information is understood as the explicit result of a design process which is the product description including drawings, CAD data or product models. Similarly, Henderson and Taylor (1993) distinguished between the "meta-physical" and the physical information of mechanical products. The first includes contents such as 'context', 'product definition units', 'alternatives', 'relations', 'constraints', 'characteristics', 'design intent' and 'decisions'. The physical information content are 'geometry', 'topology', 'features', 'form', 'materials' and 'dimensions and tolerances'.

6.2. Clustering model elements to categories of information requirements

As already shown for some needs in Table 9, an indication of the focus and granularity of each model can be achieved by matching the model elements with the information needs. Therefore we counted the number of elements of each model and how many of those elements were "consumed" in matching the needs (Table 10 & 11). 624 elements were extracted from the 16 models and 69% have been assigned to 50 categories of information needs. From these tables, it is clear that some models can map (nearly) all of their elements to actual information needs. The complete set of elements described by Baxter and Gao (2006) and Baxter et al (2007) can be mapped to a subset of the information needs; 91% of Grebici et al (2009)'s elements can be readily mapped, as can virtually all (96%) of the Pro2Kon elements. All five elements of Taura and Kubota's (2009) work can be matched up easily with information needs using only the given examples in their paper; for practical use, it would be necessary to create additional instances of their element objects in order to cover a useful set of information needs. Similarly with IPPOP, FBS-PRRE, PPM and STEP/PLCS some model elements are too abstract and generalised for direct matching, but specific instances could be derived from these elements and increase model coverage. Delving deeper into the STEP hierarchy would also increase model coverage by accessing additional elements at a finer granularity level. In the cases of MOKA (73% elements used), NIST (43% elements used) and STEP/PLCS (64% elements used) where there is a significant coverage of information needs and a significant number of "leftover" elements, some of these unassigned elements are more focused on managing the meta-information of a model instantiation and so cannot be directly allocated to information needs, though they do serve their proper purposes. Indeed all of the models, which have a clear computational intention, have such leftover meta-information elements.

Table 10: Percentage of model elements used by information needs categories (models with element definitions)

	Models **with** definitions									
	1 Chro.	2 NIST	3 MOKA	4 IPPOP	5 FBS-PPRE	6 PPM	7 CoMoDe	8 Pro2Kon	Ø	STEP PLCS
Elements Consumed	20	43	40	29	17	15	20	25	26	36
Total Elements	25	99	55	58	32	27	25	26	43	56
Consumption	80%	43%	73%	50%	53%	56%	80%	96%	66%	64%

Table 11: Percentage of model elements used by the covered information needs (models without element definitions)

	Models **without** definitions							
	9 Baxter et al.	10 Grebici et al.	11 McKay et al. 2001/ 2009	12 Nomaguchi et al.	13 Shah et al.	14 Taura, Kubota	15 Zhong et al.	Ø
Elements Consumed	36	49	13/16	19	40	5	13	23
Total Elements	26	54	20/26	31	63	5	16	31
Consumption	100%	91%	65%/62%	61%	63%	100%	81%	78%

6.3. Core categories of information requirements

In order to propose a set of core information categories which should be considered by future integrated models, we set the following thresholds: We included those categories which appeared in at least 50% of the models or 50% of the empirical studies which makes a threshold of either 8 models or 4 studies and we computed the product of the frequency of appearances in the integrated models identified and the appearance in empirical studies with a minimum of 24 ranking points. The additional constraint of a minimum of 24 ranking points as the product of the number of appearances in both samples prunes out potential 'outlier' categories, which meet one 50% threshold but have low or no occurrences in the other type. The threshold is essentially a combination of a majority test with a minority threshold. A higher quantitative threshold of e.g. to two thirds (66%: 5 studies or 11 models) would further reduce the core set to only six core categories while a 50% threshold in both samples would provide a set of ten core categories. Table 12 shows the results of the complete ranking based on the thresholds applied.

We propose four sets of categories: (1) a **core** set of 22 categories which meet the thresholds; (2) a second set of 13 **candidate** categories which are at the edge due to fulfilling one threshold but have a low appearance in the other category (e.g. "Feedback/Suggestions": Studies=5/Model=2) or "Changes/Modifications" (S:4/M:2); (3) a third set of 28 **relevant** categories which are hardly articulated as needs in empirical studies such as e.g. "Resources" (S:3/M:6), "Failures" (S:2/M:1), or have low occurrences in models such as e.g. "Safety/Risks" (S:3/M:1) or "Software" (S:1/M:1); (4) finally, a set of six categories which represent information needs articulated by engineers in empirical studies, providing **background** information, e.g. "Marketing" (S:3/M:0), "Peers & Competitors" (S:3/M:0), "Sales" (S:1/M:0) to engineering work, but which are beyond the engineering domain and therefore less relevant for core engineering tasks. These categories are not addressed in models.

Table 12: Information categories coverage and ranking across models and studies

Categories	Appearance in 8 Studies	Appearance in 16 Models	Ranking Score	
	50%: S=4/M=8 light grey	66%: S=5/M=11 dark grey	(n in M * n in S) Minimum = 24	
1. Component/Part	7	12	84	**Core**
2. Rationale	6	13	78	**Core**
3. Parameter	7	11	77	**Core**
4. Design Process	5	15	75	**Core**
5. Constraint	6	12	72	**Core**
6. Requirement	**7**	10	70	**Core**
7. Functions	5	11	55	**Core**
8. Material	6	7	42	**Core**
9. Geometry	5	8	40	**Core**
Options	5	8	40	**Core**
Product	4	10	40	**Core**
10. Behaviour	5	7	35	**Core**
Test	**7**	5	35	**Core**
11. Manufacture	5	6	30	**Core**
Performance	6	5	30	**Core**

Categories	Appearance in 8 Studies	Appearance in 16 Models	Ranking Score	
	50%: S=4/M=8 light grey	66%: S=5/M=11 dark grey	(n in M * n in S) Minimum = 24	
12. Calculation	4	7	28	**Core**
Features	4	7	28	**Core**
Method	4	7	28	**Core**
13. People	3	9	27	**Core**
14. Specification	5	5	25	**Core**
Functional relationship	5	5	25	**Core**
15. Difficulties	4	6	24	**Core**
16. Decision	3	7	21	Relevant
17. Design solutions	3	6	18	Relevant
Resources	3	6	18	Relevant
18. Design description	4	4	16	Candidate
19. Design documentation	5	3	15	Candidate
20. Input data	2	6	12	Relevant
Model(s)	2	6	12	Relevant
Product Life End	3	4	12	Relevant
Project(s)	2	6	12	Relevant
21. Feedback & suggestions	5	2	10	Candidate
Service	5	2	10	Candidate
22. Drawing	3	3	9	Relevant
23. Costs	4	2	8	Candidate
Changes / Modifications	4	2	8	Candidate
Legislation	4	2	8	Candidate
Orga. Processes & Structure	2	4	8	Relevant
Timeline	2	4	8	Relevant
24. Design Criteria	3	2	6	Relevant
25. Assumptions	4	1	4	Candidate
Plans	4	1	4	Candidate
As-delivered	2	2	4	Relevant
Technologies	1	4	4	Relevant
26. Safety & Risks	3	1	3	Relevant
27. Failures	2	1	2	Relevant
As-built info	1	2	2	Relevant
Design reviews	2	1	2	Relevant
Supply chain	2	1	2	Relevant
Software	1	1	1	Relevant
28. Maintenance info	6	0		Candidate
29. Standards	6	0		Candidate
30. Reliability	5	0		Candidate
31. Reports, records (non-design)	4	0		Candidate
32. Design for Reuse;	3	0		Relevant
End-User Support;	3	0		Background
Marketing;	3	0		Background
Peers & Competitors;	3	0		Background
Terminology, Glossary, Def.	3	0		Relevant
33. Achievements	2	0		Relevant
Correspondence	2	0		Relevant
Learning's	2	0		Relevant
Patent	2	0		Relevant
34. Best Practice	1	0		Background
Meeting Minutes	1	0		Relevant
References	1	0		Relevant

Categories	Appearance in		Ranking Score	
	8 Studies	16 Models		
	50%: S=4/M=8 light grey	66%: S=5/M=11 dark grey	(n in M * n in S) Minimum = 24	
Sales	1	0		Background
Stakeholders	1	0		Background
Technical Publication	1	0		Relevant
Legend: **Core** = Core Set / **Candidate** Categories / **Relevant** categories / beyond engineering domain, but **background** information needs				

7. Findings and Discussion

The comparison of both the integrated models from literature and the empirical studies of information needs revealed that a sizable fraction of industry's information requirements are met. Industry-led initiatives (e.g. STEP/PLCS at 41% of covered needs) and industry-academic collaborative projects (e.g. MOKA at 30%, NIST at 28%) have a higher coverage of industry's information needs than almost all their academic counterparts (where the proposed diagrammatic model of Grebici et al, 2009 at 45% and IPPOP at 29% are the frontrunners). Further comparison excluding categories which could be considered beyond the engineering domain (e.g. "Marketing") or generic (e.g. "Correspondence") shows an increase of average coverage to 27%/30% with maxima at 55% (Grebici et al, 2009), 38% (MOKA), 36% (IPPOP) and 34% (NIST).

The contrast of the proposed 22 categories as a core set of categories for future integrated modelling with the 16 models shows that seven out of 16 models cover more than two thirds of the needs with the highest being 95% by the diagrammatic model (Grebici et al, 2009) followed at 82% by Shah (1996) and 77% by Baxter (et al, 2007) (Table 8) while MOKA (73%), NIST and IPPOP (both 68%) and STEP/PLCS (55%) reach lower coverage of the core set (see Table 7 – Core 22). For academic researchers, closer attention to industrial practice when deciding what to include in models might help to increase the adoption and impact of future modelling research.

The variability in the granularity and specificity of how particular models addressed individual information needs was revealed in the number of elements "consumed" to cover a particular need, for example whether it is a single element for rationale or a complete set identifying the issue, proposed solutions, arguments for and against, supporting justification and the final outcome. The more computational models contain elements whose purpose is to ensure the smooth working of the model rather than satisfying information needs, which reduced their element consumption percentages. Models with more abstracted elements were harder to match against information needs because the specific required instances of the elements do not exist in the model definition; in practice, an application of these models would necessitate creating these derived elements, which could then be assigned to more of the information needs, increasing the model's coverage. This is reinforced by models where some element types are abstract objects; a model user can instantiate these to specific aspects (as found in other models) and thus achieve greater consensus between models. This is, however, no longer using the model in an "off-the-shelf" or "out-of-the-box" fashion; from a practical perspective, such models are harder to apply in industry because of the need to instantiate and extend rather than having the elements ready for use. The absence of commonalities due to differences in the models' emphases is further illustrated by the following examples (Table 9). A core category such as "Behaviour" is operationalized with one model element in NIST while MOKA distinguishes further between 'dynamic' and 'static behavior' while "Constraint" is not considered in MOKA but has two entities assigned in NIST. Similar clustering of model elements to needs could be observed for categories such as "Design process" (in 15 models with 1 to 5 elements), "Feature" (in 7 models with 1 to 5 elements) and "Parameter" (11 models with 1 to 4 elements per model).

In contrast to some agreement in addressing the proposed set of 22 core categories, the analysis also demonstrated an extremely narrow consensus at the syntactic and semantic level among the models drawn from the literature. Out of 300 different terms used in all models, only three terms (“Function”, “Behaviour”, “Resource”) form the most commonly used syntactic terms (Table 4) with further differences on the semantic level of three other core terms (see Table 5 & 6). Covering a time span of over two decades of modelling activities, the lack of consensus on model element definitions is surprising, given the commonality of the object of study. It may be due to the models’ different aims and objectives (Table 3), despite all being intended to capture knowledge and information: NIST models aim for the optimisation of the information flux by providing the right information to the right person at the right time; MOKA and Pro2Kon aim at capturing and structuring the knowledge in order to retrieve and revisit it; IPPOP and PPM aim to avoid redundancy and inconsistency of information by providing a referential and shared model for and by different users in the enterprise; CoMoDe aims at managing the coherence of the ongoing process, by providing a unified and common model and expressing the rules related to the product and different disciplines, and so on.

Language barriers may have proven a barrier during the early research, isolating the research teams. However, in a similar study, Shahin et al. (2009) compared nine architectural design decision models and identified a consensus on capturing and documenting ’rationale’, ‘constraint’ and ‘alternatives’ of decisions. Other elements identified without consensus were ‘problem’, ‘group’, ‘status’, ‘dependency’, ‘artifact’, ‘consequence’, ‘stakeholder’ and ‘phase/iteration’. A similar result of marginal consensus was observed in an analysis of the use and evolution of the core terminology of international standards in the manufacturing enterprise domain (Loehrlein et al.

2006). The analysis of the meaning of 'function' by Chandrasekaran and Josephson (2000) also identified differences in the understanding of this concept.

The review of the references used in the model papers shows that empirical research is referenced in about a quarter of the model papers reviewed. Empirical research is used in general to support the requirements (e.g. IPPOP for collaboration (Robin et al., 2007), for process modelling (Baxter et al. 2007), to point to the costs of information search and potential benefits of reuse (Qureshi et al., 1997), for the understanding of engineering tasks (Badke-Schaub and Frankenberger, 1999) or information behaviour in engineering (Busby, 1999). Half of the model papers use case study data or pilot software implementations to illustrate or to test their models. None of the model papers links to results from empirical studies about information needs. The content needs expressed in user studies have not been linked to the models proposed by engineers. The reason for this omission could be an implicit understanding that modelling methods are generic approaches which are tested in prototyping efforts and could satisfy the articulated user needs if required. The citation analysis of studies about information needs shows that, research about ontologies to support information retrieval references these results to support their research motivation. The engineering and software research community is focused on developing methods and tools for capturing and exchange of data and information or to support document retrieval. Research into information needs is not yet perceived as guiding such developments.

It can be argued that there is no need for a common set of elements but instead in practice a translation mechanism between different modelling approaches. This is not without its challenges as the efforts by all CAD system vendors show (Pratt 2005). A syntactic and semantic understanding is required to underpin any mapping of model elements, which is rendered difficult by those models which fail to disclose element definitions (only nine of the sixteen models provided these definitions). As the review showed, the models also have different scopes and degrees of granularity. Translation is likely to encounter omissions in the model or inflict “element overloading” where one or more incoming elements are forced into mapping to a single receiving element, which may be syntactically or semantically a weak match.

The advantage of a core set of information elements based on needs from engineering practice would be a lower risk of misunderstanding among researchers and practitioners involved in engineering design work. Given todays’ global, distributed, multi-cultural/multi-lingual service and supply chains, a common set is beneficial not only for the exchange of data, which is the stated aim of STEP/PLCS, NIST and MOKA, but also for information and knowledge exchange within and between distributed engineering teams (Maier et al. 2009). Despite the speed of electronic data transfer, distributed engineering work still requires human-based communication. Engineers spent 40.37% of their daily working time in collaborative tasks and still a considerable amount searching for information (14.2%) either from other people (7.8%) or information resources (6.4%) (Robinson, 2010). Such communication and searching activities will also benefit from such a core set of information elements.

The proposed core set of information categories is supported by at least half of the models or empirical studies. Most of these elements represent classical engineering design information elements such as “Component/Part”, “Functions”, “Geometry”, “Behaviour” or “Features” (Table 9 and 12). Six of the 16 models cover at least two thirds of these core elements. Elements which capture information beyond the manufacturing stage of the product-life cycle such as “Maintenance” (S:6/M:0), “Changes/Modifications” (S:4/M:2), “Feedback/Suggestions” (S:5/M:2) and “Product-Life End” (S:3/M:4) are candidate core elements, which have been seldom addressed in modelling efforts. This could be due to (A) product-service modelling research has not yet engaged in modelling efforts linking integrated models, (B) or vice-versa that integrated modelling efforts have not been extended towards these aspects of the product life cycle and (C) only a few empirical studies have addressed information needs from a maintenance and service perspective (Jagtap et al 2007, Heisig et al. 2010, Jagtap and Johnson 2011).

Further useful categories from the candidate and relevant sets to be included into the core set would be “costs” (S:4/M:2) as engineering design determines a large share of the final product costs as well as “Safety/Risks” (S:3/M:1) due to product usability considerations. In regards to the need to comply with legal framework and product reliability, useful categories would be “Legislation” (S:4/M:2), “Standards” (S:6/M:0) and “Patents” (S:2/M:0) but also again “Safety/Risks” (S:3/M:1). A third group of additional elements which are related to the core element “Rationale” and therefore could be legitimately included are “Assumptions” (S:4/M:1) and “Decision” (S:3/M:7).

In the context of changing business models towards product-service offerings, we suggest that this core set is enhancing previous differentiations made by Henderson, Taylor (1993) as ‘physical’ and ‘meta-physical information’ and Kimura, Suzuki (1995) regarding ‘background’ and ‘foreground information’ towards a ‘core set’ and an ‘enhanced set’ of information categories. Previous research (Heisig et al. 2010) showed that categories outside the core engineering and product life cycle scope are useful (e.g. “Sales”, “Marketing”), but might not become a core requirement in all applications.

In terms of the limitations of this research, the literature search focused on English language journal and conference contributions. Although the authors were able to examine original descriptions published in French, German and Spanish, there might be relevant contributions from other authors not yet published in English. A second limitation relates to the access to model descriptions and the limited degree of disclosure of model information, specifically the definitions of classes and attributes in the literature. Eight of the sixteen models identified did not disclose the definitions of model elements, constraining the opportunities for cross-comparisons and hindering the ability to match elements to needs. A final limitation can be seen in the assignment of the same importance to each model and empirical study to determine the core elements.

8. Conclusions and future work

The aim of this paper was to identify the core information elements required to satisfy engineering information needs and whether existing models possess these elements. The contributions of this paper are as follows: (1) the identification of 15 extant integrated models from the engineering design research community through a systematic literature search; (2) the inter-model analysis of elements which revealed the lack of consensus regarding the content and understanding of shared model elements; (3) the comparison of industry's information needs as evidenced by eight empirical studies against the models, which showed significant variability in model coverage with industry-inspired and –led models aligning more closely with industrial requirements; (4) a proposed list of core and candidate information categories (drawn from models and empirical studies, the latter requiring further confirmation by research) for use in future modelling work and as a basis for information and knowledge exchange in global communication within and among engineering teams; and (5) as a basis to extend previous distinctions made (Henderson, Taylor 1993, Kimura, Suzuki 1995) towards a core and extended engineering information reflecting the changes towards product-services.

For practitioners, the proposed list should be used as a checklist or "aide memoire" (Heisig et al. 2010) to prevent misunderstandings among members of distributed engineering teams in different companies, locations and cultures and help to overcome the problems of 'inflexible data bases' in engineering design work (Henderson 1991). The importance of such support is further underlined by the large share of daily working time spent on 'face-to-face' interaction (31.6%) (Robinson, 2010).

In summary, we can observe a core set of categories which are required and addressed in several integrated modelling efforts. A second set of candidate categories and a third set of relevant categories appropriate for engineering research have been derived from this comparative analysis. If we understand engineering work as problem-solving, information processing work in a socio-technical context using IT-devices but also engaging in social communicative interaction, the challenges future research should address are the boundaries between the 'explicit' world of engineering information and data exchange and the 'verbal' sphere of interaction of the actors involved in engineering work.

Future work should test and further validate the proposed set of core information categories by different approaches – as suggested earlier, there are a number of information needs that could legitimately be in the set, but failed to make the cut because of under-representation in studies or models. Empirical studies should test and refine the categories by in-depth interviews and focus group discussions with engineers from different product life phases, functions and roles. Integrated models should be extended and enhanced to cover those needs which have been proposed and validate their useful needs in case studies with industry.

Future research should revisit the conceptual challenges underlying this study regarding 'information need', 'category of information', 'model element' etc. Recent research in information sciences (Fidel 2012, Derr 1983) has described these challenges related to the concept of information need. The evolution of the information paradigms used in this related discipline (Naumer, Fisher, 2010) should be considered for engineering research. They started with a physical view of information needs as objects to be transferred via a cognitive view in terms of 'knowledge structures of people' towards a social view where information needs are influenced by social and cultural factors that affect people's way of preferring and using information. These paradigms mirror different perspectives in engineering with data exchange between systems, the information needs of engineering tasks of individual engineers and information sharing within global, distributed culturally diverse engineering teams.

Another question which arises from the review of integrated models and the mismatch of their content and industry needs would be to investigate the adoption of models proposed by industry similar to the adoption of conceptual modelling (Davies et al. 2006). Does industry know of the academically-led models, and if so, have they been adopted in whole or in part? More generally, a study should seek to discover the nature and usages of integrated and other models in industry. For instance, the review of models revealed an early interest in capturing the design history (Shah et al. 1996) or the rationale of decisions taken by engineers. This is also a highly ranked requirement in the user needs studies. Still, the application in industry seems low given a recent UK survey (Heisig et al., 2010).

A repository of model fragments should be established in an open source format to inform and support future modelling effort in research and engineering practice. It would serve to develop a repository of practice-informed categories of information and knowledge needs to be covered by future integrated product-process and rationale models, whether these models are for direct industrial usage or for more theoretical and descriptive academic purposes. Reusing model fragments would make it easier to construct targeted models for particular applications and blended or composite models that cover a wider spectrum of information needs. For instance, the "*Rationale*" need is satisfied by 13 models, with some providing higher granularity than others due to their aims and objectives. Rather than reinvent the wheel, researchers and practitioners could adopt the more elaborated model fragments from McKay et al. (2009) "*argument supporting*" and "*argument counter*" or those proposed by Grebici et al. (2009) with "*Question*", "*Argument*" ("*Pro argument*" and "*Con Argument*"), "*Position*", "*Solution principle*" and "*Evidence*", if a structured and detailed approach to rationale was deemed useful in a future modelling application. In this way, a repository would create synergies among engineering research and researchers. Furthermore, this repository could serve to help cope with the ambiguity of core engineering concepts as described by Vermaas (2011) by providing transparency and reference.

Finally, the inclusion of the category 'people' points towards the importance of 'tacit' knowledge (Polanyi 1966, Wong, Radcliffe, 2000, McMahon et al. 2004) which is not yet codified or not codifiable. Future work should also address the intersection between explicit and implicit elements of information and knowledge needs in engineering. This will help to better position the different tools to support information and knowledge exchange, understanding their limitations and the benefits of the 'right' combination to support engineering work.

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Annexe 1 – Literature search

Table 1: Search keywords		
1. product model	2. process model	3. rationale model
4. product life cycle	5. product data	6. product development
7. rationale	8. rationale capture	9. design process
10. integrated model	11. ontology	12. traceability
13. design history	14. process modeling	15. taxonomy
16. product modeling	17. information capture	18. knowledge
19. reuse	20. lexicon	21. behaviour
22. retrieval	23. product information	24. product design
25. design rationale	26. generic models	27. integrated documentation
28. design activity	29. design activity representation	30. information

Table 2: Search strings	
1. *product model* AND *process model* AND *rationale model*	2. *Product information AND reuse AND knowledge AND rationale*
3. *Product data* AND *design rationale* AND *process model*	4. *Information capture AND rationale AND product model*
5. *Product life cycle* AND *process model* AND *rationale*	6. *rationale model* AND *design process* AND *ontology*
7. *rationale caputre* AND *design process* AND *product model*	8. *design history* AND *product development* AND *product model* AND *rationale*
9. product model AND *traceability* AND *ontology*	*10. Integrated model* AND *design process* AND *rational capture*
11. Product design AND *taxonomy* AND *rationale model*	*12. Product design* AND *taxonomy* AND *tracebility*
13. Product model AND *taxonomy* AND *tracebility*	*14. Product data* AND *taxonomy* AND *tracebility*
15. Integrated model AND *taxonomy* AND *tracebility*	*16. Product life cycle* AND *ontology* AND *tracebility*
17. Product life cycle AND *ontology* AND *rationale*	*18. Product life cycle* AND *product model* AND *rationale*
19. design history AND *product development* AND *product model*	*20. Product modeling* AND *process modeling* AND *knowledge* AND *design process* AND *rationale*
21. Product model AND *lexicon* AND *knowledge* AND *design process* AND *rationale*	*22. Product model* AND *process model* AND *rationale* AND *knowledge*
23. Product model AND *design process* AND *behaviour*	*24. Product model* AND *design process* AND *behaviour* AND *rationale*
25. Product model AND *design process* AND *behaviour* AND *retrieval*	*26. Integrated model* AND *design process* AND *behaviour* AND *retrieval*
27. product model AND *information* AND *rationale*	*28. Integrated model* AND *information* AND *process model*
29. Integrated model AND *information* AND *process model* AND *rationale*	*30. Product data* AND *process design* AND *capture*
31. Product data AND *process design* AND *capture* AND *information*	*32. Product data* AND *process design* AND *capture* AND *information*
33. integrated documentation AND *product model* AND *process model*	*34. integrated documentation* AND *product model* AND *process model* AND *rationale*
35. *integrated documentation* AND *generic model* AND *rationale*	36. *generic model* AND *design process* AND *product data*
37. *generic model* AND *design process* AND *product data* AND *rationale*	38. *generic model* AND *design process* AND *product data* AND *knowledge capture*
39. *generic model* AND *design process* AND *product data* AND *design activity*	40. *design activity representation* AND *product model* AND *rationale*

Table 3: Electronic Databases	
INSPEC	Inspec is a leading bibliographic database providing access to the world's scientific literature in electrical engineering, electronics, physics, control engineering, information technology, communications, computers, computing, and manufacturing and production engineering. The database contains over 11.2 million bibliographic records from scientific and technical journals and conference proceedings. Approximately 600,000 new records are added to the database annually. Online coverage is from 1969 to the present, and records are updated weekly. Inspec is produced by the Institution of Engineering and Technology (IET).
Compendex	Compendex is the most comprehensive bibliographic database of engineering research available today, containing over ten million references and abstracts taken from over

	6,000 scholarly journals, trade magazines, conference proceedings and technical papers. The broad subject areas of engineering and applied science are comprehensively represented. Coverage includes nuclear technology, bioengineering, transportation, chemical and process engineering, light and optical technology, agricultural engineering and food technology, computers and data processing, applied physics, electronics and communications, control, civil, mechanical, materials, petroleum, aerospace and automotive engineering as well as narrower subtopics within all these and other major engineering fields.Online coverage is from 1970 to the present. More than 650,000 new records are added to the database annually from over 190 disciplines and major specialties within engineering. Compendex is updated weekly to ensure access to critical developments in your field.
Source (16.06.2012):	http://www.engineeringvillage.com/engresources/databases.jsp?dbid=cpx,ins,pag

Annexe 2 – Definitions of shared terms

- **Chromosome Model – Andreasen 1992a,b; 2012**

"Function is organs' and activities ability to realize an active effect. The Chromosome Model falsely proposes a function structure domain, but functions are behavior and therefore belong to the organ domain as a class of properties. Function is central for function reasoning in identifying organs (solutions)." (Andreasen 2012)

Behavior is the organs and activities way of realizing functions and properties. In the models behavior may be represented as mode of action. (Andreasen 2012)

Structure is the system model's characteristic and representation. Three structures are presented: Structure of use activity, of organs and of parts. Each of these entities and their relations has specific characteristic brake down frameworks. (Andreasen 2012)

The **design process** can be described as a process in which an abstract problem formulation in terms of a `need' is successively transformed into a manufacturable product description. (Malmqvist 1997)

- **Product and Process Model – Harani 1997**

Function is what the artefact does. It is considered as a nature of a viewpoint and inherits the "nature" class attributes.

Behaviour equation: describes the continuous/discrete behaviour of the product. The discrete behaviour is represented by the status: created, modified, designed, or destroyed. The behaviour is characterised by 2 static attributes: Id and name, and by its status.

Resource is necessary for the task to be carried out. They are mainly method-based resources. A resource is defined by the attributes: Id, Name, Functionalities and status.

Process is a task sequencing defined by diverse sequencing operators (seq, and, or) to realize different configurations. A process could have a starting task which is structured. The process is characterised by the attributes: Id, Name, Pre-conditions, Starting-date and ending-date.

Task is the elementary element of the process. A task transforms input into outputs. A variant regarding the structure of the tasks. It is characterised by the following attributes: Id, Name, Description, preconditions, post-conditions, exception rules, and behaviour

- **MOKA <u>M</u>ethodology and software tools <u>O</u>riented to <u>K</u>nowledge based engineering <u>A</u>pplications – Stokes 2001**

The **Function** View defines the functional decomposition of the product and identifies how the elements of this decomposition are to be realized by principles of solution and technical solutions.

The **Behaviour** View includes a state model view of the various states of a product (e.g. stowed, deployed, in transit), and the transition from one state to another and the constraints that each state represents on the design.

Task / Activity (the definition of sequence and method, seven top-level generic tasks)

The **Structure** View defines the decomposition of a product's structure into assemblies, parts, and features. This view can be used to represent physical, logical, or conceptual structures at any stage of the design

- **IPPOP Integration of Product – Process – Organisation for engineering Performance improvement – Girard, Castaing, Noel 2002, Bettaieb 2005, Robin, Girard (in Press),**

Function links at least two components through interfaces. It is a relation between components. A function defines the objective to be achieved within some threshold defined by a criterion and its goal value. A function is characterized by the attributes: name, Id and type.

Behaviour defines a modal state inside the lifecycle of the product and is defined by a set of components, interfaces and functions. A behaviour is defined as the bridge linking the structure to its function. Behaviours are characterized by the attributes: name, ID and type.

Resource describes the set of the hardware/software, methodological, informational, and human resources needed for the completion of a task or project. A resource is characterized by its type.

Process model describes the progress that leads to the elaboration of the product model. The progress is partially ordered / planned and is composed of activities.

Activity or Task is defined in terms of its type (project, task, or elementary task), inputs, outputs, the required resources for its accomplishment, and conditions and constraints to fulfil. A process is decomposed into tasks and a task is decomposed into elementary tasks, recursively. A task is characterised by the ID, and name.

- **FBS-PPRE (Product/Process/Resource/External Effect) – LaBrousse 2004**

Function describes in an abstract way the ultimate goals of an object (process, product or resource). It is characterized by its description and its ID.

Behaviour describes the dynamic of an object. It consists of a set of rules and laws (continuous models) as well as of a sequential suite of states (discrete models) representing the evolution of a structure after applying a given impulsion (or stimulation) during the process.

Resource is an object (material, energy, software or human) which is exploited in order to satisfy objectives, but unlike the product, the resource is not a result/output of the process.

Process is a sequential, spatial, and hierarchical organization of a set of activities, using resources (or means) and leading to products (or outputs), e.g. the manufacturing process and the control process, etc. A process is characterized by its number.

Structure is intrinsic to an object, and independent from its role. It allows the specification of the elements that comprise the modelled object as well as these elements' attributes. An element could be a product, a function, a process or a resource. A structure is referred to by a reference number.

- **NIST Models (CPM, OAM, DAIM) – Sudarsan et al. 2005**

Function: The artifact's function represents what the artifact is supposed to do. The artifact satisfies the engineering requirements largely through its function. The term function is often used synonymously with the term intended behaviour.

Behaviour: The artifact's behaviour represents how the artifact implements its function. Behaviour is governed by engineering principles which are incorporated into a behaviour or causal model that explains how the intended function is achieved. Application of the behaviour model to the artifact describes or simulates the artifact's observed behaviour based on its form.

- **Pro2Kon Model (Prozess + Produkt + Konfiguration) – Chasiotis 2006**

Process model: Superior class of all development processes.

(Design Step / Calculation Step): Single step of the design process. Single step of the calculation process.

Product (structure): The complete product or a variant of it.

- **CoMoDe – Collaborative Model for capturing and representing the engineering design process – Gonnet, Henning, Leone 2007**

Actors: They conduct the execution of activities and operations by having specific purposes, or pursuing certain objectives, while attempting to satisfy one or more requirements.

Activities: They are the tasks that are carried out during design processes, such as proposing a given separation structure, analysing whether such structure satisfies the separation targets that were imposed, evaluating its economic potential, or deciding among alternative separation schemes if the process system's engineering domain is considered.

Annexe 3 – List of all terms

- Chromosome Model – Andreasen 1992a, Malmqvist 1997, Malmqvist, Schachinger 1997

Design process, Functional requirements, Functions, Properties, Constraints, Objectives, Means, Processes, Organs, Components, Feature/Form, Parameters/dimensions, Material, Surface quality, Tolerances, Solved_by relations, Alternative_solutions relations, Requirements_on relations, Decomposition, Required secondary functions, Parametric requirements, Ad of higher-level constraints, HasInfluenceOn relations

DESIGN SPECIFICATION: requirement; PRODUCT CHROMOSOME: Process structure, Function structure, Organ structure, Component structure; FUNCTION-MEANS TREE: Functional requirements, Objective, Constraint, Means; PROPERTIES: Evaluation, Property value, Test procedure, Computational model, Subj. Assessment; LIFE-PHASE SYSTEM: Lifephase system

- Product and Process Model – Harani 1997

Behavior equation, Composition link, Constant, Description, Equivalence Link, Link, Method of Equation Resolution, Nature, Nature of Parameter, Nature of Viewpoint (Function, Behaviour, Structure), Node, Operator, Parameter, Parameter Computing Method, Parameter Computing Method-Formula, Parameter Computing Method-database, Parameter Computing Method-Rules, Design Process, Product Concept, Resource, Sequencing operators, Specification Link, State, Task, Transition, Variable of Behaviour, Viewpoint Concept.

- MOKA Methodology and software tools Oriented to Knowledge based engineering Applications – MOKA (2000), Stokes 2001

MOKA Consortium (2000) KBE Coupling Illustration Deliverable D3.4. MOKA META MODEL, p. 22-48

Activity, Alternatives_Set, Atomic_Structure, Behaviour (abstract), Behaviour_Operand_Detail, Behaviour_Operator, Comparison, Composite_Shape, Composite_Specifier, Composite_Structure, Constraint_Evaluation, Derived_Structure, Dynamic_Behaviour, Element_Instance, Element_Kind, Element_Property, Element_Selection, Event, Expression_Node, External_Operand, Function, Instantiation, Knowledge_Role, Operator_Node, Operand_Detail, Operand_Node, Operand_Value, Operator_Detail, Original_Structure, Platform, Primary_Shape, Principle_of_Solution, Process_Operand_Detail, Process_Operator, Property_Value, Record_Set, Replica_Structure, Requirement_Comparison, Shape, Shape_Operand_Detail, Shape_Operator, Shape_Specifier, Simple_Specifier, Spatial_Role, State, Static_Behaviour (or constraint), Structure, Structure_Instance, Structure_Operand_Detail, Structure_Operator, Structure_Property, Task, ask_Activation, Technology, Technology_Kind, Technology_Operand_Detail, Technology_Operator, Technology_Property, Technology_Role, Transition.

Stokes, M. (2001) 'Managing Engineering Knowledge. MOKA: Methodology for Knowledge Based Engieering Applications', New York: ASME Press.

Activity, Assembly, Behaviour, Complex Geometry, Composite Features, Compound Activity, Context Description, Design Description, Design Rationale, Domain Theory, Dynamic knowledge categories, Elementary Activity, Feature, Finite Elements models, Function, Geometry, Goals, Manufacturing Process, Material, Part, Principle_of_Solution, Product, Representation, Requirements, Simple Geometry, State, State Model, Strategic Knowledge, Task, Technology, Technical Solution, Transition.

- IPPOP Integration of Product – Process – Organisation for engineering Performance improvement – Girard, Castaing, Noel 2002, Bettaieb 2005, Robin, Girard (In Press)

Action levers, Activity or Task, Actor, Alternative component, Alternative function, Alternative Interface, Association/Link, Attribute Type, Behaviour, Centre, closure iteration, Collaborative Project, Collaborative Task/Activity, Common Component, Common Function, Common Interface, Component, Constraint, Core Type, Decision centre, (Decision) Criteria, Decision framework, Decision Variable, Department, Design centre, Design framework, Dynamic class Entity, Frame, Function, Group, Hardware/Software resource, Human resource, Indicator (Performance), Information, Information Link, Informational/Methodological resources, Interface, Iteration, Justification, Level, Maturity, Milestone, Modelled entity, Objective/Goal, Plant, Product data, Project, request-vote (Vote-Request), Resolution iteration, Resource, Status, Transition, Trigger, Value, View Component, View function, View Interface, Vote iteration.

- FBS-PPRE (Product/Process/Resource/External Effect) – LaBrousse 2004

Assembly, Behaviour, behaviour law, Enterprise object, Entry-state, Exit-state, Expected behaviour, Effect external, Feature, Function, Input/Output, "link ass-obj", Link Str-Obj, Manufacturing Process, Nature of an object, Object, Object Role, Performance indicators, Principle of solution, Process, Product, Process pattern, Real behaviour, Representation, Resource, Service functions, State, Status, Structure, Succession, Technical functions, Triggers, Variable of decision.

- NIST Models (CPM, OAM, DAIM, etc.) – Sudarsan et al. 2005; Fenves et al. 2004

Artifact, Artifact Association, Assembly, Assembly Association, Assembly Feature, Assembly Feature Association, Assembly Feature Association Representation, Assembly-Relationship, Authority, Behavior, Case, Catalog, Common Core Object, Common Core Relationship, Component Family, Component Series, Component Version, Composite Feature, Configuration, Connection, Constraint, Core Entity, Core Property, Datum, Datum Feature, Design Evolution Rationale, Design Evolution, Design Justification Evolution, Design Justification, Design Rationale, Development Specification Evolution, Development Specification, Dimensional Tolerance, Directed Set-Relationship, Entity Association , Evolution, Evolution Rationale, Family, Family Derivation Rationale, Family Derivation, Family Designation, Feature, Feature of Size , Fixed Connection, Flow, Form Tolerance, Form, Function, Functional Model, Geometric Tolerance, Geometry, Idealization , Intermittent Connection, Kinematic Pair, Kinematic Path, Kinematics View, Location Tolerance, Mapping, Master Model, Material Condition, Material, Movable Connection, OAM Feature, Orientation Tolerance, Parametric Assembly Constraint, Pareto Optimal Surface, Part, PFEM Artifact, Port, Position Orientation, Principle, Product Family, Product Series, Product Version, Profile Tolerance, Rationale, Reference, Regulation, Relative Motion, Requirement, Rule, Run out Tolerance, Series Derivation, Series, Set-Relationship, Shape View, Size, Specification, Statistical Control, Strength View, Technology, Tolerance, Trace, Trade-Off, TransferFunction, Undirected Set-Relationship, Usage, Version Derivation, Version,

- Pro2Kon Model (Prozess + Produkt + Konfiguration) – Chasiotis 2006

Calculation method, Calculation model (general) (Berechnungsmodel), Calculation model (specific) (Rechenmodel), Calculation process, Calculation step (Rechengang), Cax-System, Component, Configuration, Design method, Design process, Design step (Gestaltungsgang), External process, Gestalt model, Individual Parameter, Parameter, Process model, Product, Project related Parameter, Prooftesting method, Prooftesting model, Prooftesting process, Prooftesting result, Result model, Standard Parameter, User, User-Project

- CoMoDe – Collaborative Model for capturing and representing the engineering design process – Gonnet, Henning, Leone 2007

Activities, Activity Types, Actor's Goals, Actors, Argument, Artefact, Basic Activities, Compound Activities, Design Object Types, Design objects, Design Project, History, Individuals, Model version, Object Version, Operation Types, Operations, Position, Position Attribute, Position Value, Requirements, Resolution, Skill, Teams, Version.

- PLCS Concept Model (Eurostep 2010) www.plcs.org (accessed 11.3.2013)

Activity, Activity_actual, Activity_method, Activity_planned, Analysis, Approval, Baseline, Breakdown, Certification, Classification, Condition, Context, Contract, Date_time, Document, Effectivity, Environment, Functional_breakdown, Id_alias, Information_right, Interface, Justification, Location, Message_envelope, Observation, Part, Person_organization, Physical_breakdown, Planned_product, Product, Product_definition, Product_group, Product_individual, Product_individual_version, Product_version, Project, Property, Realized_product, Representation, Requirement, Resource, Risk, Scheme, Skill, Slot, State, State_definition, State_observed, System, System_breakdown, Task, Trigger, Verification_and_Validation, Work_order, Work_request, Zonal_breakdown, resource_item,

Models without definitions of elements

- **Baxter, Gao 2006, Baxter et al. 2007:**

alternative (solutions), component/part, cost, constraints, decisions, design documentation (formal), features, functionality, geometry, drawing (component images), input, material, method, parameter, people (contact details for specialists, project team members), performance, problems, project, rationale (design intent), report, requirements, , organisations (customers), in-service (process type), solutions (previous, abandoned), supply chain, tasks and, test, guidelines, environment and country.

- **Grebici et al. 2009:**

RATIONALE DOMAIN: Rationale 1, Question 1.1, Factual 1.2, Past design 1.2.1, Current design 1.2.2, Argument 1.3, Pro Argument 1.3.1, Con Argument 1.3.2., Position 1.4, Solution principle 1.5, Evidence 1.6;

PROCESS DOMAIN: Design Process 2, Life-cycle phase 2.1, Task 2.2, Decision 2.3, Activity 2.4, Analysis 2.4.1, Constructive 2.4.1.1, Explanatory 2.4.1.2, Synthesis 2.4.2, Evaluation 2.4.3, Resource 3, Technology 3.1, Tool 3.2, Machine 3.2.1, Software 3.2.2, Method 3.3, Human 3.4, Representation 4, Domain-specific 4.1, Physical structure 4.1.1, Geometry 4.1.2, Analysis/test/log 4.1.3, Procedural 4.2;

PRODUCT DOMAIN: Issue 5, Product lifecycle 5.1, Development 5.1.1, Manufacturing/assy. 5.1.2, In-service operation 5.1.3, Failure measurement 5.1.3.1, Failure effect 5.1.3.2, Disposal 5.1.4, Product characteristic 5.2, Functioning/fault 5.3, Product and manufacture 6, Physical phenomenon 6.1, Physical effect 6.2, Material 6.3, Product structure 6.4, System 6.4.1, Assembly 6.4.2, Component 6.4.3, Part 6.4.3, Product feature 6.5, Physical feature 6.5.1, Dimension 6.5.1.1, Geometry 6.5.1.2, Functional feature 6.5.2, Interface feature 6.5.3, Attribute (expected/predicted/observed) 6.6, Product 6.6.1, Process 6.6.2, Interface/environment 6.6.3:

SPECIFICATION DOMAIN: Specification 7, Function 7.1, Elementary 7.1.1, Composite 7.1.2, Requirement 7.2, Constraint 7.2.1, Criteria 7.2.2, Functional 7.2.3, Other 7.2.4, Cost 7.3.

- **McKay et al. 2009:**

DESIGN RATIONALE: issue, rationale definition, answer proposed, answer accepted, answer rejected, argument, argument supporting, argument counter: PRODUCT DEFINITION LINKAGES: context, product reference, product definition aspect, product type, reference to product definition, relationships between definition aspects: PRODUCT, PROCESS STRUCTURES: item, element structured, element relationship structure, item relationship, process step, part, composition, connection, type, statement, material flow, information flow.

- **McKay et al. 2001:**

specification_schema, product_specification_definition, product_requirement_group, product_requirement, requirement_value, context, condition, life_cycle_phase, part_aspect_schema, requirement_-context, relationship_between_aspects, aspect_of_part, geometric_aspect_of_part, material_aspect_of_part, other_aspect_of_part, part_type attribute, state_schema, state, state_relationship, people.

- **Nomaguchi et al. 2004:**

Decision, design process, problem, suggestion, evaluation, alternatives, issue, drawings, CAD models, figures, conceptual product models, customer’s requirements, functional requirements, meta-level operation, design tools, Position, Argument, argument supports, argument objects, Emphasis, Product, Aspect, Element, parameter, Relation, Parameter, Aspect relation, design operation, design stage, Action level, operation primitive.

- **Shah et al. 1996:**

PRODUCT DATA: Specification of attribute to the design (e.g. shape, size, material), Assembly relations, Configurations of different versions, Bill of materials/parts list for each version, technological parameters, product structure, geometry, tolerances, features, technological parameters;

DESIGN PROCESS / STEPS: sequence of steps, or actions change the state of the design, or the state of the designer, Classification of desing steps into specific types (decomposing, analyzing, calculating, gathering data, etc.), Relationships between design steps at different levels of abstraction, temporal aspects of design steps (sequence, parallelism, iteration), information about who (or what entity) performed each design step and when it was performed;

RELATIONSHIP OF DESIGN STEPS TO PRODUCT DATA: what objects provided input to the design step, what objects were modified as a result of the design step, what objects where created as a result of the design step;

RATIONALE: Constraints, decisions, design choices, reasons, Issues, alternatives, arguments,

product version, part, ‘as specified’, ‘as designed’, ‘as manufactured’, feature data, application feature model, parametric feature model, representation feature model,

process object meta-class, type of the process (in the process hierarchy), purpose/function of the design process of step, duration of the process (start, terminate times), enacting entity (who or what performs the process), status of the process (working, committed, abandoned, suspended, resumed, failed, etc.), description of the procedure or steps that make up the process, entities that are input (used) to the process, entities that are output (created, modified) from the process, design rationale for the design process/step, constraints affecting the design process/step, Design Representation Language (DRL), Design process entities, Primitive design activities (operations), Design tasks - composite design processes, Design subproject, Product data entities, Design constraints, Functional units, Assemblies / subassemblies / component composite product data, Person, Design group - a group of persons working on common design tasks, Higher-level organizational structures (department, company etc.). Decision making entities, Issue, list of alternatives, selection made, Rationale, with pros and cons for that alternative.

- **Taura and Kubota 1999:**

INFORMATION MODEL: Action, Object, Alternative, Constraint (specification and past action), Reason (teleological and causal).

- **Zhong et al. 2006:**

design tasks, Design intent, process model, process architecture, activities, descriptions of input and output flow, constraint condition, rules for process execution, status of flow, distribution of role, resource, design tasks, reason of design change and iterative process, projects, method, technology.