# Managing a Complex Interdisciplinary Engineering System using Feature Models

by

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## Abstract


In order to assist in the management of complex engineering design tasks, a famework is proposed which allows for the formal modelling and coordination of design activities as a Cyber-Physical System. Unified feature models are used to define the design tasks employed in the design process, and these models are coordinated using design structure matrices. These techniques allow for design managers to optimize the sequencing and coordination of design activities in a way that minimizes the size and cost of design iterations, while improving design quality.

The methods proposed are explored in the context of activities used for the design of downhole tools used in the extraction of heavy oil. The complexity of this system is explained, and a functional decomposition is used to define and justify the design tasks which are included in the model. Generic features are presented which define the mechanical system (design features), the interactions between the system and the environment (phenomenon features), and engineering design tasks which can be used to model the system and optimize the design (evaluation features). The relations and dependencies between all of these elements are mapped, and a Design Structure Matrix is used to explore how the design process can be optimized by rearranging the tasks, coupling or decoupling tasks, and identifying opportunities to improve the system by focussing on those dependencies which can be shown to negatively impact the performance of the system (or the cost of the design process).

The proposed framework provides the requirements and design structure for a software tool which can, when implemented, be used as a stand-alone design tool, or as a high performance physics engine to enable the systematic and accurate estimation of critical parameters in conjunction with existing commercial system-level models.

## Preface

The research conducted for this thesis was performed in conjunction with an ongoing collaborative research and development program sponsored by RGL Reservoir Management and under the supervision of Principle Investigators Dr. Jingli Luo, Dr. Hongbo Zeng, Dr. Carlos Lange, Dr. David Nobes, and Dr. Alireza Nouri. The nature of the collaborative program is described in Chapter 1. Many of the works published in this collaborative effort were referenced extensively in this thesis: All references to these works have been properly cited and included in the bibliography.

Chapter 3 of this thesis has been published as Michael Leitch, Yishak Yusuf, Yongsheng Ma, "Interdisciplinary semantic model for managing the design of a steam-assisted gravity drainage tooling system," *Journal of Computational Design and Engineering*, Volume 5, Issue 1, 2018, Pages 68-79. This paper was a detailed expansion of a conference paper presented by Mr. Yishak Yusuf. I was responsible for preparing the final manuscript, including extensive edits of Mr. Yusuf's conference paper and the creation of additional sections, as well as integrating additional research. Mr. Yusuf and I collaborated on the creation of additional figures. Dr. Yongsheng Ma was the supervisory author and was involved with the concept formation and manuscript composition.

## Dedication

This thesis is dedicated to my grandfather, Angus Ronald Steveson Leitch, who graduated as a Master of Science in Chemical Engineering from the University of Alberta in 1956.

## Acknowledgements

Thanks first and foremost to my supervisor, Dr. Yongsheng Ma for his patience, guidance, and support over this long program of study. You and I have been through a lot in getting this program off the ground.

Thanks to Mike Claerhout, Brent Fermaniuk, Jarek Bialik, and the management team at Regent Energy Group/RGL Reservoir Management for providing financial and technical support during my studies. Special thanks to Mike Claerhout for providing invaluable professional mentorship during my tenure at RGL.

Thanks to Dr. Carlos Lange, Dr. David Nobes, Dr. Jingli Luo, Dr. Hongbo Zeng, and Dr. Alireza Nouri for your ongoing support of the collaborative research project, and for your willingness to work with me on a variety of initiatives over the course of my studies.

Thanks to the researchers who contributed to the many studies that were coordinated as part of the collaborative research effort. Special thanks to Yishak Yusuf and Lei Li, who have been especially generous collaborators and friends during my studies.

Thanks to the National Sciences Engineering and Research Council, the Department of Mechanical Engineering, Department of Chemical and Materials Engineering, and Department of Civil and Environmental Engineering, and the Facutly of Engineering at the University of Alberta for your financial, administrative, and strategic support to RGL's research efforts.

Finally, thanks to my family and friends whose encouragement and unfaltering support kept me buoyed throughout this process.

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# 1 Introduction

The management of engineering design processes poses significant challenges for engineers and managers, especially when the complexity of a given system requires the input and coordination of many different expert domains. Often, these different expert disciplines have coupled or conflicting requirements, and aligning these disparate requirements in service of a singular design problem is the central challenge of systems engineering. Traditional organizational structures rely on a large, centrally managed, network to coordinate design tasks and manage the various domain experts. Alternatively, where the domain experts are distributed and independent, partial solutions may effectively solve part of the design challenge, but may not work efficiently with other parts.

This thesis demonstrates how knowledge management methods and information technology toolsets can be used to coordinate the work of domain experts, effectively replacing the traditional organizational structure while ensuring that the various design models developed by independent and distributed groups of experts can efficiently solve the greater design challenge.

The design of an optimized production system for SAGD enhanced oil production is used as a case study to demonstrate these methods, with a team of academic researchers used to model the distributed expert system, and a small oilfield services company providing the coordination of experts around a central problem with significant complexity. The underlying hypothesis motivating this work is that significant industrial value can be created through the coordination of these academic efforts with minimal overhead. The proposed framework, based on feature modelling techniques, can easily be applied to other design challenges where multi-disciplinary collaboration is required.

This work contributes to the field of cyber-physical systems (CPS), showing how dependencies and relationships between elements of a complex system can be mapped and coordinated, and how very specific expert systems can be integrated into system level models. It demonstrates the potential of such CPS methodologies using the SAGD oil production design effort, leveraging and consolodating intelligent yet disparate expert systems to reduce uncertainty and improve accuracy in modelling the behavior of this very complex multi-physics system.

### 1.1 Scope & Organization of Thesis Project

This thesis demonstrates how feature modelling techniques can be used to solve complex design problems. Specifically, it shows how decentralized networks of subject experts can be coordinated using a digital toolset and knowledge management techniques. These methods are used to model a research program which seeks to optimize the design of an advanced oil production system. The underlying theories of both knowledge management and enhanced oil recovery are presented, and each of the expert areas is described in detail. Finally, the unified framework for coordinating the design effort is presented.

This thesis project has consisted of 3 major efforts:

1. The development an industry-supported academic research project, designed to take advantage of the expertise of several academic collaborators, is described. The structure and strategy of the program is outlined, as well as the various groups who have contributed to the program.
2. The body of work completed by this team of researchers over the first two years of an (anticipated) five-year long effort, resulting in a number of publications which have contributed to the design efforts of the industry sponsor. These works are described at a

high level, with reference to their associated publications, and it is shown how these contributions can be modelled as design features.

3. The formal modelling framework which was developed to coordinate the design effort around the design of tooling to enhance the performance of SAGD heavy oil extraction. A journal paper has been published which describes this framework at a high level. This paper is included in Chapter 3, with the remainder of the thesis expanding on this work.

Implementation of the software tool described in this thesis was beyond the scope of this project. The UML models presented provide a level of detail which will allow for the implementation of this software tool as a follow on effort, following the workflow presented in Section 4.7. In addition, the methodologies and tools used here can be readily employed in other cyber-physical contexts involving complex multideisciplinary phenomena.

## 1.2 Background

The efforts underlying this thesis began in 2012 with an Engage grant administered by the National Sciences and Engineering Research Council (NSERC). The Principle Investigator, Dr. Yongsheng Ma, installed a small team in the offices of RGL Reservoir Management, at that time called Regent Energy Group, to assess the business for opportunities where research collaboration may be mutually beneficial. Several major findings emerged from the effort:

- The design domain in which the firm operates is of high complexity, with many fundamental phenomena contributing to the short and long-term performance of the product.

- There existed an industry-wide lack of understanding of the details of the design domain in which the firm operated.

- The design efforts of the firm could benefit from high level research & development, and especially investigating complex inter-dependencies between fundamental phenomena.

- The firm was eager to assert themselves as domain experts by filling the existing knowledge gap.

- The firm was not large enough to resource a sizable research & development effort internally.

Based on these findings, a scope of work was developed for an industry-academic research & development collaboration between RGL Reservoir Management and the University of Alberta. This scope of work would eventually be formalized under four independent (but related) Collaborative Research and Development (CRD) grants administered by NSERC. These four grants were approved during the 2014/2015 academic year, and the efforts of these groups are ongoing at the time of this writing (J. Luo & Zeng, 2015; Nobes & Lange, 2015; Nouri & Chan, 2015; Zeng & Luo, 2015)

### 1.3 Research Sponsor

RGL Reservoir Management is an oilfield services company specializing in the design and manufacture of down-hole tools used in Enhanced Oil Recovery (EOR), headquartered in Edmonton, Alberta, Canada. With approximately 150 employees, it is considered a Small-Medium Enterprise, but has a worldwide sales footprint and has built and operated manufacturing facilities in Canada, the United States, Oman, and Colombia.

RGL built its business in the design and manufacture of slotted liner, a type of perforated pipe which is commonly used to filter sand from produced fluids in oil wells, water wells, and gas wells. They hold several patents for technologies related to slotted liner manufacturing, and possessed strong competencies in mechanical design, having designed and built their own manufacturing facilities and production equipment. They had also developed an internal design model used to specify the design parameters of slotted liner to suit a target well's geological properties. However, it was recognized by RGL's management team that there was a great deal more to be learned about how to improve the performance of their products, and a great deal of opportunity for growth in embedding higher level knowledge into the design and application of their products.

### 1.4 Research Hypothesis

The technical challenge to be addressed by this work relates to enhancing the ability of designers to couple expert models, both experimental and computationally based, in service of a complex problem. Building and enhancing networks of systems are a focus of Cyber-physical Systems (CPS) research (H. Chen, 2017), and the methods sought by this paper will enable the alignment of high performance models regardless of spacial orientation, model scale, and modelling technique. It is the hope that as these methods mature they will further enable the more effective use of sensing technologies, further coupling the physical to the digital and enabling even greater performance enhancements (Trappey, Trappey, Govindarajan, Sun, & Chuang, 2016).

The case in focus for testing the CPS moedelling technique involves the performance and reliability of downhole tools used in Enhanced Oil Recovery techniques, and specifically, Steam-Assisted Gravity Drainage (SAGD) for the extraction of oil from oil sands. The SAGD domain will be described in detail in Section 3.2, but in brief, the technique involves the use of steam to lower the viscosity of heavy oil within the reservoir, and extracting the hot oil from the reservoir while leaving the sand in place. These systems suffer from several issues including plugging, corrosion, process failure, and mechanical failure, and mitigating any of these issues involve complex and costly interventions. Existing reservoir analyses use the concept of "skin" as a factor to correct for the various near-wellbore failure modes as a lumped correction factor. While several works propose mathematical and semi-empirical models to describe skin damage in more detail, they tend to rely on empirically determined factors to repreaent each root cause, which cannot adequately describe the underlying phenomenon, synergistic effects, or transient behavior of the skin. Our goal is chiefly to improve the accuracy and reduce uncertainty in the SAGD model, and in particular in accurately modelling the near wellbore behavior.

The underlying hypothesis of this research and development effort is that by developing a comprehensive understanding of the complex phenomenon in the vicinity of the downhole tools (the near-wellbore region), the behavior of the system can be more accurately and precicely modelled, enabling the development of tools with improved performance and longevity, and the refinement of system-level simulations to enhance the long term performance of the system. It is also understood that due to the complexity of the SAGD domain, that the appropriate depth and breadth of understanding must call upon the expertise of several expert domains, and that adequate understanding of the SAGD domain must unify the work of these expert domains. It is expected that feature management techniques can be used to manage the work of these expert domains by:

1) identifying opportunities for collaboration

2) managing the collection and dissemination of expert knowledge and

3) coordinating the order of operations in such a way that the risk of rework is minimzed.

### 1.5 Research Program Design

The research collaboration undertaken by RGL Reservoir Management and the University of Alberta required careful planning and negotiation in order to generate the required support by the administrations of both institutions. Examining the features of the resulting program structure is instructive, as it both guides and lends support to the knowledge management techniques that should be used in the management of any such complex design system.

The three major stakeholders in this project are RGL Reservoir Management (RGL), the University of Alberta (UofA), and the National Sciences and Engineering Research Council (NSERC). RGL provided seed funding to the program as well as a commitment to in-kind support equal to the seed funding. The in-kind commitment included full-time engineering support, manufacturing support, and ongoing access to expert engineers and management. RGL also provided the research context, demonstrated the commercial value of the research, and provided an avenue for the commercialization of the research activities. The University of Alberta provided research talent, in the form of professors, post-doctoral fellows, and graduate students, as well as access to government funding which would match RGL's cash and in-kind contributions. The National Sciences and Engineering Research Council provided funding to the program through several Collaboative Research and Development Grants (Nobes & Lange, 2015; Nouri & Chan, 2015; NSERC, 2018; Zeng & Luo, 2015). These grants are intended to drive economic development in Canada by incentivizing collaboration between Canadian universities and private partners; extending the research capabilities at Canadian universities in industrially menaingful ways; provide meaningful training for "Highly Qualified Personnel"; and improve the likelihood of academic research being commercialized (Government of Canada, n.d.).

### 1.6 Progress to date

At the time of writing the collaborative reseach program has yielded 58 publications, six peer reviewed journal papers (several others are in draft stage as of the time of writing), and provided enough material to host 2 industrial research symposia which provided a venue for RGL to share the research findings and directions, as well as receive feedback from, members of it's industry network. The program has employed up to 34 HQP at one time (at Master's, PhD, and PDF level). Three former HQP have been hired by RGL to date, and RGL maintains an additional 2 full-time-equivalent engineers collaborating on the research program.

While these numbers may not be direct indicators of commercial success, it represents a significant body of work in a niche field, and RGL's presence in the research community has positioned them as experts in that niche. This research progam has also manifested in the creation of an industrial testing lab, and the development of commercial software. Both of these results aim to commercialize the knowledge generated by this expert system.

# 2 Engineering Informatics and Unified Feature Theory

Complex engineering problems typically require a great deal of effort and resources to manage effectively. The principal objective of design engineering is to maximize design quality, which can be defined as maximizing the degree to which a design meets the problem it was designed to solve while minimizing the cost of the effort. Because so many different solutions can be brought to bear on complex problems, the "solution space", or collective set of potential solutions, can be vast from the outset. Bradner et al notes that even moderately complex design problems can have extremely large solutions sets, referencing a study by Flager et al, 2009, which considered the design of a single room building with $55 \times 10^6$ possible solutions (Bradner, Iorio, & Davis, 2014). Computational power is widely recognized as an effective tool (and with increasing complex problems, an essential tool) in managing such vast solution sets. to assist in the identification, analysis, and selection of design solutions (Bradner et al., 2014). However, it is also recognized that computational support is weakest in the early stages of solution generation, where the creative cognition of a designer cannot currently be matched by machines (Bernal, Haymaker, & Eastman, 2015). At this stage solutions can be novel and unpredictable and where creative exchange among a team of experts can "transcend participants' expertise and expectations" (Bowen, Durrant, Nissen, Bowers, & Wright, 2016).

We can define the objective of design engineering research as the exploration of the power of cognitive processes and the limitations of human designers, in the contet of the opportunities afforded by developments in computational design algorithms. Sobek and Jain summarize the various design activities as problem definition, idea generation, engineering analysis, design refinement, and nondesign activities of project management, report writing and presentation preparation (Sobek & Jain, 2007). Taking the cross section of these broad stages we can see 2 different angles with which to approach the system: one from the cultivation of expert knowledge, and one from the management and orientation of expert systems working towards a common goal. Adams et al described such a bifircation, identifying an intersectionality between content (ie. Expert) knowledge and pedagogical knowledge, which they termed “Pedagogical Content Knowledge”. Their objective was to identify ways to improve the quality of feedback delivered during design reviews, and recognize the synergy beteween what they termed “conceptual knowledge” and “procedural knowledge” (Adams, Forin, Chua, & Radcliffe, 2016).

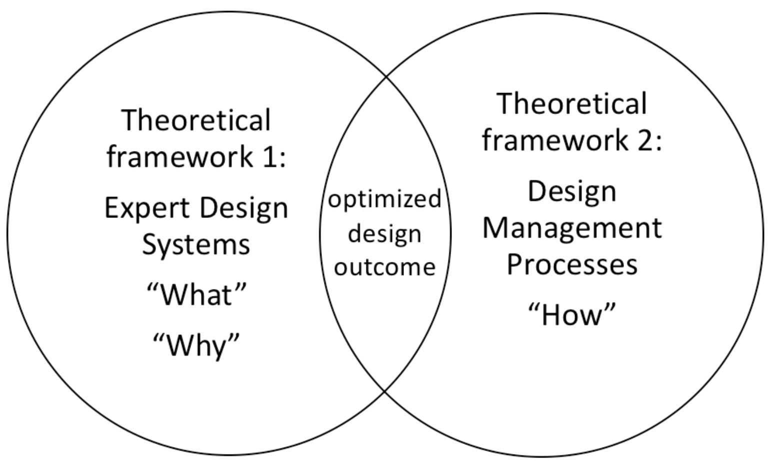


Figure 1 Intersectionality between expert systems and design processes. Adapted from (Adams et al., 2016)

This thesis attempts to formally map the “conceptual” or “creative” or “expert” systems which are responsible for the generative work of problem solving (ie the “what” and “why”), onto the “procedural” or “process” or “coordinating” systems which are responsible for organizing the expert systems in a way that maximizes design quality (ie the “how”). The remainder of this chapter will review the theory of design process, as well as the theory which underlies the intersection and coordination of the design process with the various expert systems that may be brought to bear.

Management processes and structures have traditionally focussed on the systems of human experts and the processes required to organize them. The field of engineering informatics deals with the systems and processes required to organize engineering information and knowledge within these systems. Knowledge capture and reuse has emerged as a critical aspect towards both design optimization and in the development of ever more sophisticated expert engineering software systems to model increasingly complex phenomena with great accuracy and low cost. This chapter will describe the engineering design and management processes that have historically been applied to design teams, as well as emerging engineering informatics strategies. This will set the stage for the presentation of an engineering informatics model based on unified feature theory that will enable the coordination of human, empirical, and simulated expert systems to solve complex engineering problems.

## 2.1 Organizational Approaches to Design

The processes used by organizations to control engineering design processes typically follow a linear-sequential stage gate approach. The linear-sequential nature is not to defeat the iterative nature of problem solving, but as part of a broader organizational philosophy, based on accountability, that relies on strict methodology among workers and institutions, believing that standardization and repetition leads to fewer defects. The Toyota Production System (TPS) is a famous and successful example of this philosophy of quality permeating the entire organizational culture. Fundamentally, the TPS empowers workers to do their jobs with great care and precision, focusing on minimizing waste (called Muda in the TPS, it includes both material and organizational waste) and continual improvement (Kaizen) (Toyota (GB) PLC, n.d.). Toyota understands that such a culture is difficult to grow and sustain (Surowiecki, 2008). Not only does Toyota train its workers and managers in the TPS philosophy, using repetition of structured lists, mantras, and mnemonic devices to embed its core concepts, it has explicitly linked promotion at the organization to individual's abilities to embrace TPS principles (Spear & Bowen, 1999). Toyota's methods led to a worldwide embrace of the concepts of just-in-time and Lean manufacturing.

Six Sigma, a concept trademarked by Motorola in the 1980s but brought to prominence when it was adopted by GE in the 1990s, focuses on the elimination of defects: six "sigmas", or standard deviations from the mean of a normal distribution equates to 3.4 defects per million. DMAIC, part of the Six Sigma methodology, lays out the problem solving sequence: Define, Measure, Analyze, Improve, Control (or Sustain) (de Mast, 2007).

Product development literature tends to focus on solution pathways more tailored to the progression of solutions from abstract to tangible: 1) Definition of requirements; 2) Conceptual Design; 3) Detail Design; 4) Testing & Refinement; 5) Product hand-off (or mass production) (Ulrich & Eppinger, 2003). The various structures used to coordinate design activities are explored in the next section.

In an effort to streamline the communication process and enable more efficient work among individuals, the structure of the organization defines the nominal lines of communication among individuals. These relationships, whether they be reporting relationships, financial arrangements, or spatial relationships (Unger & Eppinger, 2009), tend to influence the frequency and substance of information that passes between individuals, regardless of their function (Sosa, Eppinger, Pich, McKendrick, & Stout, 2002). Traditional organizations are organized by either functional groups or project groups with managers overseeing individuals and teams with either a particular functional skillset or project interest (Ulrich & Eppinger, 2003). It is widely recognized that some level of collaboration across these silos is generally required, and in any case being able to formalize, communicate, and reuse lessons learned across projects & disciplines allows for greater value to be realized from the organization's collective institutional knowledge. A great deal of research has gone into devising and evaluating structural strategies to accommodate knowledge capture, management, and resuse. The concept of a matrix organization, which gained popularity through the 1970s and persists today, was designed to formalize such cross-enterprise communication (Davis & Lawrence, 1978). Matrix structures enable organizations to form multidisciplinary teams in an agile way, and formalize relationships between individuals who are expected to interact during the problem solving process. deKraker explores how matrix organization is an enabler of concurrent engineering to support reductions in product development timeline and improve quality, explores how information technology can be used to support the complexities of concurrent engineering (deKraker, 1997). Attempts at matrix-supported concurrent engineering goes by different names in different sectors: In recent years "Centers of Excellence" have been a way for corporations to identify and formalize initiatives which cut across stand-alone business units; In software develoment "Agile" is a philosophy of extreme concurrency.

Organizational structures can be formulated to try to take advantage of predictable communication lines or obvious dependencies, putting experts and teams more likely to have to share information in close proximity. Several researchers have noted that problem solving is more efficient when team members interact face-to-face (Allen, 1984; Braha, 2002; Rasoulifar, Eckert, & Prudhomme, 2014). Co-location is not always practical though, and increasingly firms are becoming more dependent on inter-company collaboration, relying on distributed networks of experts to achieve business goals. Given the theoretical ease of remote work in the modern workplace, it should be able to realize the benefits of combining the talents of different experts without having to bear the cost and complications of co-locating those experts. Groysberg and

Slind suggested that it isn't the spacial relationship which is the key to effective collaboration, but rather the "mental and emotional proximity" (Groysberg & Slind, 2012).

Most of the organizational strategies described above were developed and are implemented in the context of large organizations which can support relatively large numbers of managers and organizers. For smaller firms, or companies in industries with very tight margins, implementing such programs is not an option. For companies with inconsitent cash flows it is essential to be able to scale up the workforce relatively quickly at the start of a project, and scale down upon completion. Rolstadas et al discuss four project organization models through the lens of risk management (Rolstadås, Hetland, Jergeas, & Westney, 2011). The four organizational models differ in the need for up-front specificity in the performance and quality expectations, and in the need for operational overhead to manage the project: The *Turnkey* concept pushes the majority of project risk onto a 'turkey contractor' who is responsible for delivering the project to the specified design, but it can be expensive and difficult to modify the project specifications after the project is initiated: Where there is a great deal of uncertainty in the outcome, this is a risky model. The *General Contractor* concept retains ownership for the engineering, while pushing implementation onto a single contractor to manage project execution. This model allows for concurrency in project design and execution. *Multiple prime contractors* allow for greater concurrency while increasing the need for careful management of engineering changes, schedules, and performance expectations, and importantly, the project owner must coordinate the flow of information. The *Ad-hoc alliance* is the least centralized of all of the models, and relies on the project owner coordinating a network of resources, each of whom has access to the others and communication between network members is expected.

Taken to the extreme, such ad-hoc or distributed organizational systems can accomplish remarkable things. Open-source software (and hardware) development, crowdsourcing schemes such as incentive competitions, and open-access trends in the research community all provide ecosystems where ad-hoc alliances can be formed and leveraged to meet needs without relying on burdensome project management organizations. In all of these cases, designers must be very careful to formalize the design intent, set expectations for quality, and manage changes.

Quality standards such as ISO 9001 (International Standards Organization, 2015) and industry-specific qualifications like API Q1 have become common tools for formalizing verifiable design and development processes. ISO 9001, in particular, emphasizes three main features of a Quality Management System: Defining the processes used to create, change, and measure the product or service being offered; Defining the requirements of the product or service being offered; and Requiring the verification and validation of the product or service being offered, to ensure it meets the defined requirements (International Standards Organization, 2015). Use of such standards enables consistency across partners in distributed systems.

Research objects have been proposed as a more comprehensive way to encapsulate and share academic research than through paper publications (Belhajjame et al., 2014). The idea is to publish comprehensive formalized aggregations of research work-product, enabling for more comprehensive knowledge transfer between research groups. The development of ontologies and standards for communicating research object data in a consistent way is ongoing.

## 2.2 Design Management Processes

There are a great number of different strategies with which firms pursue solutions to such problems, but the efficacy of these processes is critical to industrial performance. Unger and Eppinger describe four types of risk that can be mitigated by design processes: Technical risk; Market risk; Schedule risk; and Financial risk (Unger & Eppinger, 2009). Most engineering design processes are variations on a concept, and possess similar features: system decomposition &

integration, iterative design cycles, and design reviews (Braha, 2002; Unger & Eppinger, 2009; Wynn & Eckert, 2016). System decomposition referrs to the process of breaking down large and complex problems, products, processes, oganizations, etc. into sub-systems, sub-sub-systems and so on until the system can be described by a set of manageable 'chunks' (Braha, 2002), each with a level of complexity that can be assigned to an individual technical expert or team for solution generation. Integration referrs to the consolodation of the chunks, sub-systems, etc. into a unified product, process, or solution. The process of decomposition and integration is often described using a V shape in Systems Engineering literature (Eppinger, 2016; Ryen, 2008). The downslope of the V follows the decomposition of the system (or process) from high level requirements into systems, subsystems, and into enough detail for the technical implementation to occur at the bottom. Integration happens on the upslope of the V, where the components are unified, tested, verified and validated before the system can be implemented.

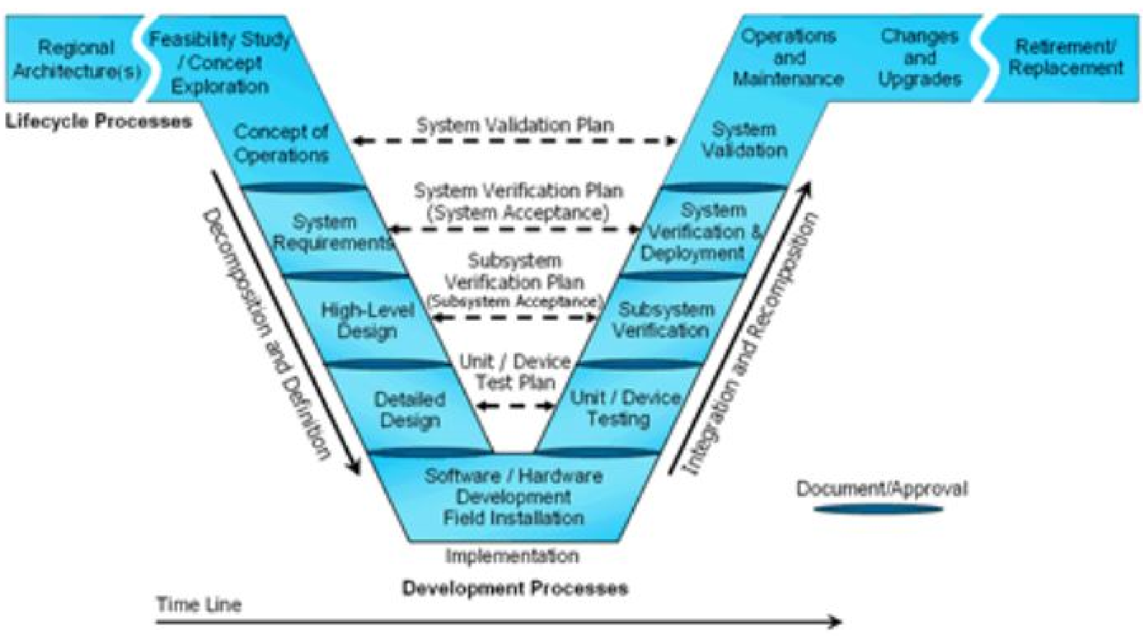


Figure 2 System Engineering 'V' from (Ryen, 2008)

Another way to characterize this decomposition-integration process is via the cognitive concepts of convergence and divergence. The TRIZ methodology, developed in the Soviet Union starting in the 1940s, translates in english to “theory of inventive problem solving”. The methodology outlines 40 “inventive principles” that are theorized as being fundamental ingredients to every solution set (Mann & Domb, n.d.). The list of principles were derived from a study of patents, and was intended to aid designers in overcoming “contradictions” in design problems. Samuel and Ohler described some of these principles through the lens of cogntive based design, recognizing design as a fundamentally creative enterprise yet one with recognizable features that can be organized and practiced systematically (Samuel & Ohler, 2015).

The decomposition-integration methodology, while conceptually clear, can rarely work in a truly linear logical-sequential way: interaction between parts of systems can fundamentally impact the global system (Guariniello & DeLaurentis, 2016), which suggests that a “fully decomposed” system cannot be treated as a system of independent design problems. In reality, the system “chunks” are often dependent, and in many instances, co-dependent on each other, with the outcomes of one design decision effecting the set of requirements or assumptions driving another design decision. Where one chunk depends on another, the design efforts are performed sequentially. Where there are co-dependencies, iteration is typically required to converge on an acceptable solution (Wynn & Eckert, 2016). Iterations are recognized, and indeed encouraged, in many engineering design processes. The Spiral model was developed in 1959 for the design of ships (Wynn & Clarkson, 2018). This is the most explicitly iterative design model possible, forcing a review of each major subsystem sequentially in order to converge on a solution. Tahera et al describe several design processes (Tahera, Wynn, Earl, & Eckert, 2018), some of which are more explicitly iterative than others. One of these processes species “Redesign” as a formal task in the process architecture. Unger & Eppinger draw the distinction between inter-phase iterations and cross-phase iterations in staged product development processes (Unger & Eppinger, 2009).

The fundamental paradox of engineering design is that while on the one hand iterations are required to optimize a system's design, on the other hand iterations represent time, effort, and cost that could be considered waste. And to make matters worse, it is often difficult to know whether iterative work is productive optimization or unproductive rework (Browning & Eppinger, 2002; Yassine, Joglekar, Braha, Eppinger, & Whitney, 2003). Research in engineering design, knowledge management, informatics, management science, systems design, and any similar field can be fundamentally described as an exercise in achieving design optimization: maximizing the quality of a design solution while minimizing the resources required for the solution's development.

Le et al. discuss how tools such as Dependency Structure Matrix can be useful to help identify iterations in project development processes, and specifically how to model the impact of process iterations on project lead time (and therefore cost) (Le H.N.; Wynn, D. C.; Clarkson, 2010). A dependency structure matrix, or design structure matrix (DSM), allows for the visual mapping of dependencies between design elements. Elements which are not dependent on one another can be addressed in parallel, while elements which are dependent should be addressed sequentially. Elements that are inter-dependent are referred to as coupled, and must be addressed concurrently or iteratively (Ulrich & Eppinger, 2003). The application and methods of the DSM concept have been detailed extensively in literature. Stephen Eppinger has written extensively on the subject, describing the use and utility of the Design Structure Matrix concept developed by Steward at a high level (Eppinger, 1991), as well as a textbook on the matter which described the techniques of DSM's in great detail alongside a number of case studies (Eppinger, 2016). His collaborators and co-authors over the years have focussed on a great deal of different methods and refinements to the concept. Much of this work is dedicated to the development of algorithms to aid in DSM partitioning, which attempts to sequence and cluster design tasks to minimize reverse-dependencies by making the matrix lower-triangle, as demonstrated in Figure 3. By identifying and grouping design elements in strategic ways, the size and cost of iterations can be managed while improving the overall design quality.

McCord identifies a “heuristic” and a mathematical approach to partitioning DSMs (McCord, 1993). Thebeau demonstrated the use of clustering routines to achieve optimized clustering of components (Thebeau, 2001). Li & Li promote the use of DSM’s to inform the assignment of components into modules, to aid in modularizing systems for assembly and reuse (M. Li & Li, 2012).

In addition to component design, Design Structure Matrices have been used to model other aspects of organizations. Browning reviews how DSMs can be used in four different applications: Component models, Team models, Activity models, and Parameter models. They further distinguish static and time-based models (Browning, 2001). The focus of these optimization

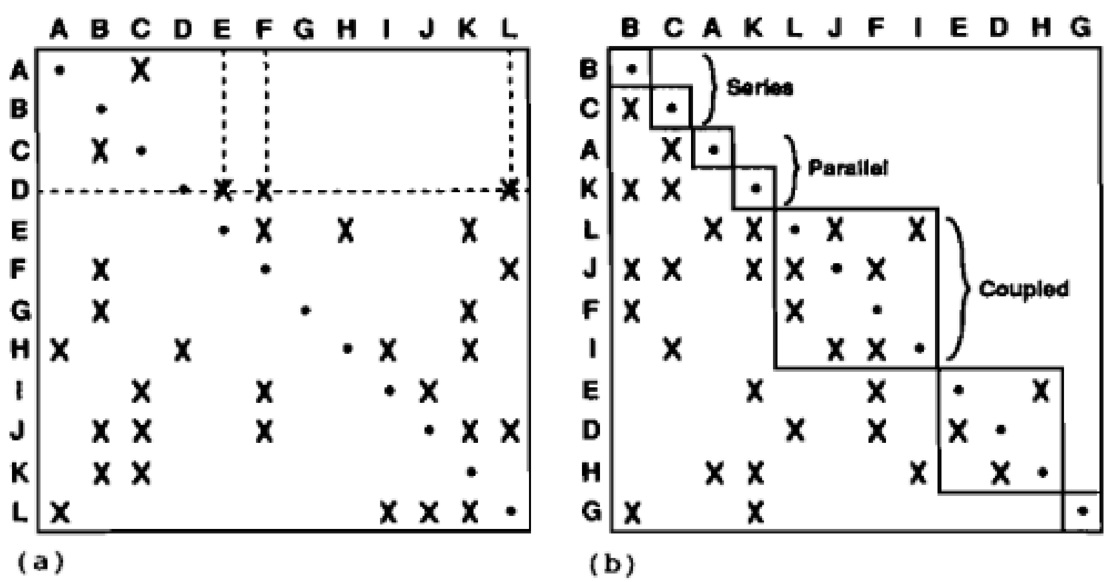


Figure 3 The design structure matrix: (a) original matrix; (b) partitioned matrix. From (Eppinger, 1991)

exercises tend to emphasize a reduction in size of iterations, but it is important to remember the value of iteration in improving quality. Krishnan, Eppinger and Whitey examine how sequential decision making can lead to a degredation of quality due to upstream decisions over-constraining downstream decisions. They suggest employing design of experiments methods to identify the "sequence invarient variables", which are those shown to have no constraining effect on downstream tasks. Identifying these variables allows for the simplification of iterations and therefore a reduced size and cost of concurrent engineering (Krishnan, Eppinger, & Whitney, 1997). On the other hand, Grogan and Weck published a study which attempts to quantify the cost of collaboration, which was shown to be significant, taking up to 60% of a team's time and 90% of their resources (Grogan & de Weck, 2016). Their results highlight the importance of design methods and tools to mitigate the cost of collaboration. Dantan et al propose reliability models as a method to quantify the level of uncertainty in design prarameters throughout the system, allowing for a simulation-based assessment of variable dependence, and early prioritization of the optimal design space (Dantan, Qureshi, Antoine, Eisenbart, & Blessing, 2013).

### 2.3 Unified Feature-based Knowledge Management

The previous sections have highlighted some of the organizational and procedural approaches to engineering design. Most engineering design approaches includes short, simple and interative progressions which begin with a statement of requirements to constrain the solution space, a series of problem solving stages to progressively narrow the solution space and converge on a solution, and finish with a quality check. It is clear that the coordination of elements within a design system (both within the system being designed and the among the actors who are responsible for designing) is important in order to constrain costs, manage risk, and guarentee quality. There is a great deal of interest in the development of new computational approaches to support, optimize, and automate the coordionation of engineering design elements.

Cyber-Physical Systems (CPS) have emerged as a paradigm to describe the integration of systems bridging the physical and cyber worlds, and enabling the consolodation of many disparate intelligence assets (Trappey et al., 2016). CPS specifically deals with the integration and interoperability of networks of systems and sensors, with the explicit aim of managing uncertainty and improving performance (Bhrugubanda, 2015). Implementing such systems is a focus of engineering informatics, and it is an area of active research and development (Liu, Peng, Wang, Yao, & Liu, 2017). Object-oriented methods have emerged as the most prominent framework for building information models (Bernal et al., 2015; deKraker, 1997; Y.-S. Ma & Tong, 2003). Eastman and Fereshetian (Eastman & Fereshetian, 1994) describe several information modelling concepts, and identify the 'object' as a conceptual container which may capture a range of complexity from low-level (such as a single part) to high-level (such as a complex assembly).

The concept of design features, or feature based design, was developed as a way of incorporating design intent and higher-level design patterns into Computer Aided Design systems, which traditionally only held raw geometric data. In the context of parametric CAD modelling, features can be used to define geometry within the context of the design function that the geometry fulfils. The geometric elements may relate to manufacturing operations: For example a feature model of a threaded hole could include the specifications for the tap drill size, hole depth, hole end condition, chamfer, and thread specification. The geometric elements may relate to the function or design intent: For example a feature model of a keyway slot could include a definition of the required machining tolerance or surface finish required for the keyway slot to guarantee proper alignment and assembly characteristics of the finished part in it's assembly. Through features, geometric attributes may also be driven by non-geometric parameters, such as strength requirement, constraints imposed by mating parts, or ergonomic considerations.

Where traditional CAD software involved the user explicitly specifying the faces, edges and vertices (Boundary representation, or B-rep), DeKraker proposed the development of feature libraries in CAD systems, where the user would select a feature geometry (from a "canonical library"), and define the validation constraints to fully define the feature (deKraker, 1997). Ma, Tang and Chen demonstrate how geometric features can be modelled using EXPRESS-G & STEP data modelling languages. Their product data model codified functional significance in addition to low level part geometry by defining the functional relationships between low level geometric details, creating a stand-alone feature which can be used across Compute Aided Engineering (CAE, or generically, CAx) applications (Y. S. Ma, Tang, & Chen, 2007). Rahman, and Ma demonstrate how semantic logic can be combined with a parametric CAD model to automate the design work required to design the drillstring for oil wells (Rahman & Ma, 2013). Wubneh presented a detailed case whereby expert knowledge was encoded in feature definitions and optimized using a neural network in order to automate the design of an excavator arm (Wubneh, 2011). These studies, among others, highlight how feature modelling conepts can be used to limit rework, by codifying expert knowledge for easy re-application elsewhere.

If features are treated as generic, and not developed with one expert application in mind, they become a very powerful tool for collaborative engineering. In particular, supporting interoperability between expert systems represents a significant challenge and opportunity (Bernal et al., 2015). Sajadfar et al defined a semantic information model with 3 layers: the Data Layer, the Semantic Schema Layer and the Application layer. The semantic schema layer extracts the data from the data layer and maps it into formal specifications using schematic schema. This Semantic Schema Layer allows for different Applications to draw upon the same dataset (Sajadfar, Xie, Liu, & Ma, 2013). Tang and Ma explore a simple geometrical feature through two contextual lenses: Design and Manufacture. They define a feature schema for for each as an Application-specific feature model, allowing different expert domains to interact with the same model dataset (Tang, Chen, & Ma, 2013).

Objects are defined by their attributes and operations (G. Chen, Ma, Thimm, & Tang, 2004), and are associated to other objects in the information model through relations (Eastman & Fereshetian, 1994). Ma et al have refined object-oriented modelling methods through their definitions of Generic Features (G. Chen et al., 2004) and Associative Features (Y.-S. Ma & Tong, 2003). Their work specifically targets issues of interoperability between Computer-Aided-Engineering (CAE) systems, and use sophisticated object-oriented information models to enhance knowledge capture and reuse in design systems (Y.-S. Ma, Britton, Tor, & Jin, 2006) and address issues around maintaining data consistency change propagation over the length of design processes (Y. Ma, Chen, & Thimm, 2008).

The Generic Feature was defined by Tang and Ma, based on the work of Chen et al, which used UML to describe a framework which was completely agnostic to expert domain or application (Tang et al., 2013). Using this abstract definition of a feature as an intermediary allows for interoperability across expert domains and applications. Tang and Ma's Generic Feature is shown in Figure 4. The Generic Feature consists of four major fields: Attributes, constraints, parameters, and topological entity pointers.

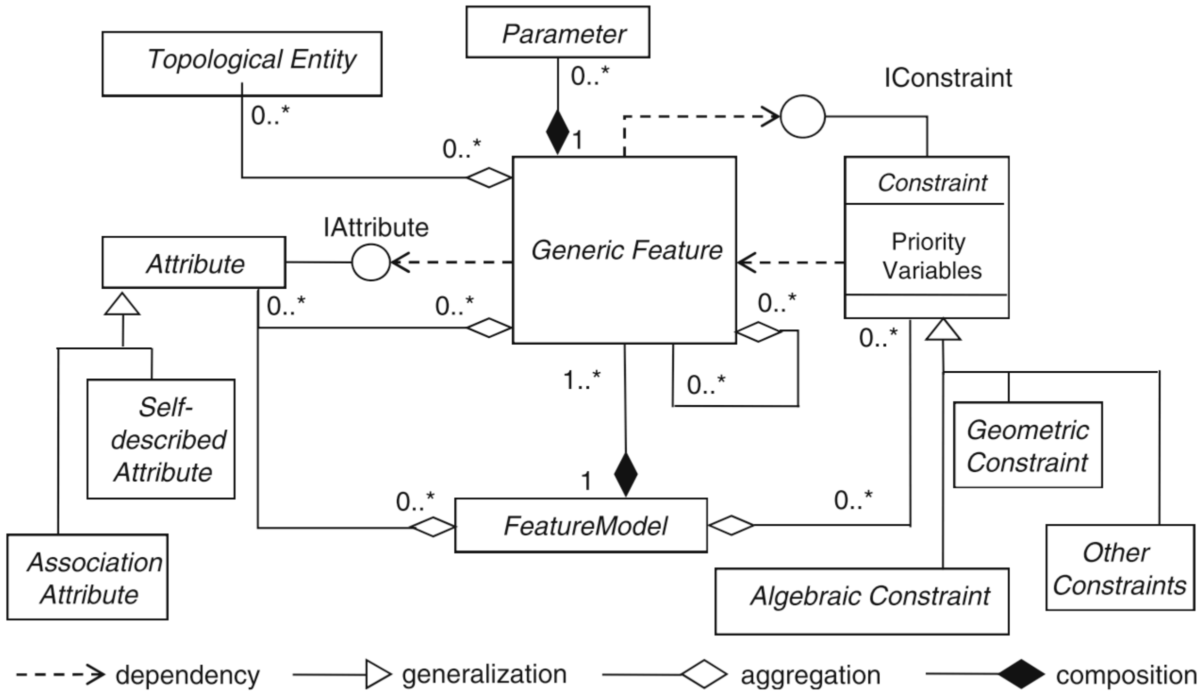


Figure 4 Generic Feature Model, From (Tang et al., 2013)

## 2.4 Conclusion

In the context of solving complex design problems through the use of many expert systems, we have explored a number of different approaches to organizing the effort. There is the organization of the individuals themselves, which may be co-located or distributed (spacially or temporaly) within a single organization or spread across a number of collaborating organizations. A variety of design processes were reviewed, which typically rely on some form of iterative rework in order to converge on a good design solution. The literature is clear that both the organizational and engineering process designs are critical drivers of both cost and quality.

The organizational structure upon which this thesis is organized requieres a de-centralized organizational structure, which by it's very nature makes unifying the design process more difficult. In order to overcome these challenges, several techniques for representing, storing, and coordinating the knowledge and efforts of expert engineers and expert engineering systems were reviewed. The next chapters will explore in detail how this expert knowledge can be represented and coordinated in the design effort.

# 3 Interdisciplinary semantic model for managing the design of a Steam-Assisted Gravity Drainage tooling System

This chapter describes the engineering application of the system of interest, and establishes the conceptual framework for the interdisciplinary semantic model being developed to manage the research described. The system of interest is the design of a production system for oil wells employing the Steam Assisted Gravity Drainage (SAGD) process, a common production technique employed in oil sands and heavy oil reservoirs. A functional decomposition of the system yeilds a number of expert areas which are then defined as Phenomenon Features. The process for integrating those systems into a complete (yet extensible) Interdisciplinary semantic model is described.

A version of this chapter was published in the Journal of Computational Design and Engineering in January 2018, with coauthors Yishak Yusuf and Yongsheng Ma (refer to Preface for the full citation). The section headings have been modified from the original publication to reflect the integration of this paper in the thesis.

## 3.1 Introduction

Building a comprehensive understanding of complex physical processes often relies on the coordination of the knowledge and methods of many different expert domains. Managing the effective flow of information in such systems is challenging, as the efficiencies gained through concurrent processing can be easily negated by excessive iterations. The development of methods to optimize such activities is an area of active research. While in some cases these systems are controlled by a central authority (i.e. the management structure of an engineering firm), many complex engineering problems are investigated in a distributed way, through formal and informal relationships between smaller organizations and individual experts each working on a different aspect of the greater problem. These distributed expert systems (DES) are common in academic research settings and in industries where fundamental problems are not yet well understood.

One such problem is the extraction of heavy oil from the oil sands formations found in Alberta, Canada. The oil sands, a mixture of unconsolidated sand and bitumen, is extremely viscous at room temperature. Shallow reservoirs are dug up and the oil is separated from sand at an extraction facility. Surface mining of these reservoirs has been ongoing in Northern Alberta since 1930, but approximately 80% of this resource is too deep for surface mining (Oil Sands Discovery Center, 2014). For reservoirs deeper than 70 meters, *in-situ* upgrading is required to separate the bitumen from sand underground, or partially upgrade, before it is pumped to surface. Most *in-situ* techniques are thermally driven, where bitumen is heated to lower its viscosity so that it flows. Alberta's oil sands are the third largest reserve of oil in the world (Canadian Association of Petroleum Producers, 2016) with, as of 2014, 166 billion barrels of proven reserves in its oil sands (Alberta Energy, 2014), and 133 billion barrels requiring *in-situ* production methods (National Resources Canada, 2017). This industry represents a giant piece of the Canadian economy with expected investments of $300 billion in Canadian *in-situ* projects between 2016 and 2036 (Canadian Energy Research Institute, 2017).

Steam assisted gravity drainage (SAGD) is the most widely used *in-situ* recovery technology for Alberta's oil sands. SAGD is responsible for nearly a third of all bitumen recovered in Alberta in 2014, and is the fastest growing extraction technology in the province with compounded annual growth of 25% (Holly, Mader, Soni, & Toor, 2014). The SAGD technique requires drilling pairs of horizontal wells through the reservoir, separated vertically by approximately 3 meters. Steam is injected through the upper well to heat the reservoir up to the point where the bitumen flows under gravity to the lower well where it is collected to be pumped to surface. These wells are expensive to install and operate, and must be expected to operate reliably for upwards of 15 years to maximize the recovery and economic payback of the resource.

There are several known phenomena that result in below-optimal levels of operation of SAGD systems. These include: fines migration, pore space plugging, sand control plugging, and steam breakthrough (Romanova & Ma, 2013)(Taubner, Subramanian, & Kaiser, 2015)(Kaiser, Wilson, & Venning, 2002) that cause failure of the wells. It has also been shown that the performance of SAGD wells is very sensitive to downhole completions design and that modular configuration design methods may be employed to achieve desired production levels (Renpu, 2011).

Understanding the root causes of these issues, and improving the design and operation of SAGD completions is an area of ongoing research. Due to the complex nature of the SAGD process, this research is typically conducted in a distributed way, leveraging subject matter experts at various institutions and leaving the integrative work to the end user (oil producers). However, progress in only one domain has limited applicability in the integrated system, and integrating the work of independent expert areas represents a significant challenge. Further, managing the development of technology from the proof-of-concept phase through to commercialization represents a significant challenge.

This paper presents a modelling framework based on cyber-physics systems (CPS) methods to manage the multidisciplinary design process that is required to effectively optimize the performance of complex systems such as those found in the heavy oil industry. The objective is to highlight a toolset which can help coordinate the efforts of distributed expert systems and simulations to most effectively manage the design process. This toolset is described in the context of a highly customized SAGD production tooling system. The resulting knowledge model aims to identify an object-oriented structure, using the unified feature modelling approach (Y. Ma, 2013), to embed the mathematical principles which govern SAGD performance within a collaborative and concurrent engineering design process. Reservoir conditions are represented from different functional viewpoints in such a way to provide substantial information for the overall design of the recovery system. Important process parameters such as oil recovery rate, steam-to-oil ratio, temperature, and pressure distribution can then be predicted and optimized based on the chosen design parameters. Making use of such simulation methods saves significant time and costs that would otherwise be spent on laboratory or field experiments.

This paper is organized into 5 sections: In section 3.2 the relevant theories and literature describing the SAGD technique are evaluated, in order determine the requirements of the system. The available modelling techniques are also evaluated. Section 3.3 describes the resulting SAGD knowledge model in detail. Classes are defined to represent the relevant phenomena using UML notation, with attributes and functions that serve to represent the functionality of the associated expert systems. Section 3.4 discusses the use and implications of the model. The chapter is concluded in section 3.5 with a summary of the significance and novelty of this work, a brief discussion of the limitations of our study and the future work required.

## 3.2 Defining the Expert Domain

### 3.2.1 The Steam Assisted Gravity Drainage Phenomenon

The Steam Assisted Gravity Drainage process involves drilling a pair of horizontal wells in the bituminous formation (oil sands), separated vertically by approximately 3 meters. The upper (injection) well is used to inject steam into the deposit to heat the bitumen to a point where its viscosity is low enough to flow under gravity, while the lower (production) well drains the hot bitumen and pumps it to the surface (Azom, 2013). The reservoir's geological properties, physical and chemical properties of the bitumen deposit, operating conditions (pressure, temperature, and injection rate of the steam), and the design attributes of the completion tooling have significant effects on the production rate (Nguyen, Bae, Tran, & Chung, 2011). Figure 5, from Gates & Larter 2014 (Gates & Larter, 2014), shows a good nominal schematic of the cross section of a SAGD horizontal well pair.

While conceptually simple, the use of steam to change the properties of the bitumen (lowering its viscosity) affects the reservoir more broadly. The changes to the chemistry and geology of the system brought about by the introduction of steam and hot water can significantly affect the nature of the multiphase flow through porous media, especially over long periods of time. Further, operators are constantly experimenting with new enhanced oil recovery methods designed to boost the performance of SAGD systems such as vapor extraction and electro-thermal dynamic stripping (Oil Sands Discovery Center, 2014). It is challenging to understand the intricate domains within this representation and when, in fact, each of these areas is the subject of significant ongoing research. Thus, a real challenge arises when attempting to depict the whole system in detail where much associative complexity is involved.

The SAGD model developed by Butler in 1994 (Butler, 1994) postulated a conductive heat transfer at the edges of the steam-saturated zone called the steam chamber. The steam chamber forms when steam is injected and expands over time to form a region that has essentially equal temperature to the temperature of the injected steam (Al-Bahlani & Babadagli, 2009). The relationship between flow velocity and oil production rate for each specific time and steam chamber shape can result from computation of material balance equations (A Azad & Chalaturnyk, 2009)(Patel, Aske, & Fredriksen, 2013). Their resulting equation is one that involves important parameters that describe the reservoir porosity and geometry. The result from energy balance calculations for a SAGD operation was the steam-to-oil ratio (SOR), a major measure of reservoir performance.

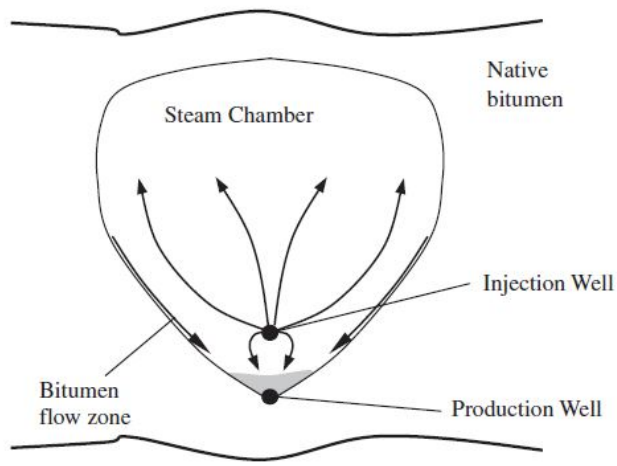


Figure 5: Cross-Section of the Steam-Assisted Gravity Drainage (SAGD) Process. From (Gates & Larter, 2014)

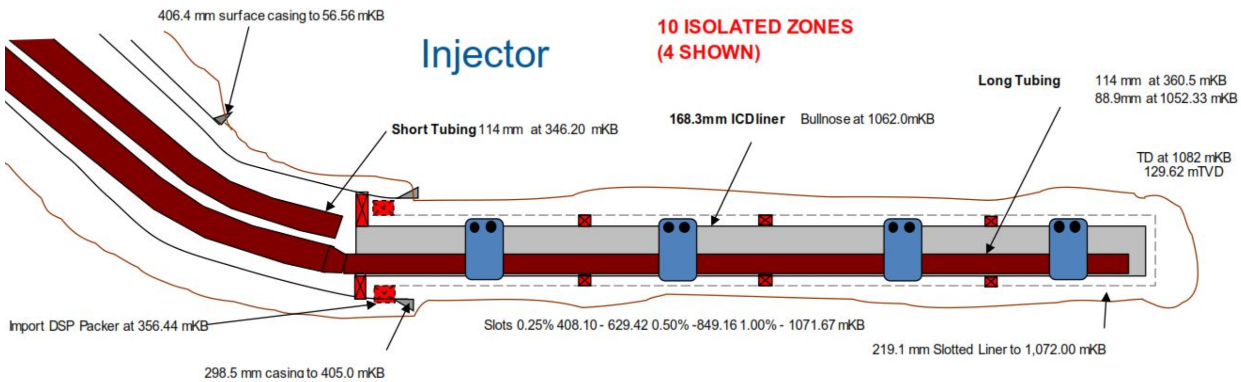


Figure 6: Flow Control Device Completion Scheme. From (*Suncor MacKay River Project 2016 AER Performance Presentation*, 2016)

Each SAGD well is completed with two functional sub-systems. A sand control completion, typically on the order of a kilometer long, is installed horizontally within the 'pay zone' of the reservoir. The sand control completion serves two functions which are to stabilize the wellbore, and filter sand from the produced fluids. Slotted liners are the most common type of sand control completions used for SAGD wells (Xie et al., 2007)(NOV, 2014)(Bennion, Gupta, Gittins, & Hollies, 2009a). A flow control completion may be installed inside the sand control completion to regulate the flow along the length of the well, change the distribution of outflow/inflow to accommodate heterogeneity in the reservoir, and prevent steam breakthrough. An example of a completion design is shown in Figure 6 (*Suncor MacKay River Project 2016 AER Performance Presentation*, 2016). A short cutaway section of a slotted liner sand control completion with notional flow control ports is shown in Figure 7. It is instructive to emphasize on the extremely high aspect ratio of these systems. Well pairs measure approximately 0.2 meters in diameter, placed on the order of 3 meters apart, along 1000 meter lengths. A typical slotted liner completion may contain more than 350,000 individual slots, each on the order of 1mm thick.

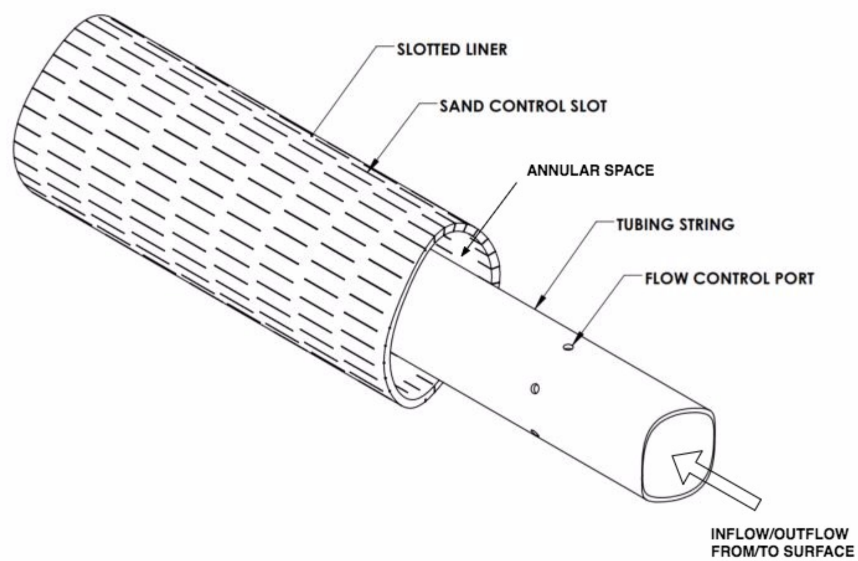


Figure 7: Completion Details (notional)

### 3.2.2 SAGD Reservoir Modelling

The full SAGD system can be represented as a block diagram shown in Figure 8. Steam is pumped into the injection wellbore where it is distributed along the sand control annulus via the flow control completion before flowing through the slots into the reservoir. The SAGD phenomenon "transforms" the steam into production fluids (a mixture of oil and water) which flow through the production sand control liner into the production wellbore. After passing the production completions equipment, it can be pumped to surface where the produced oil is received by facilities that separate water and any produced solids from it.

The major challenge in developing a comprehensive model of the SAGD system is to understand and quantitatively predict the complex and multi-disciplinary phenomenal occurrences that cannot easily be modelled experimentally. Most existing commercial models are designed to aid the specialized work of experts within a subset of the overall system and the coordination of these independent models is the central challenge of this work. The review presented in the following sections is not intended to be comprehensive across every available domain. Instead, a few major domains of active interest are surveyed in order to highlight the types of work that must interact in a unified model.

The majority of the published SAGD models focus on the transformation of steam to emulsion at the reservoir scale. Drainage models proposed by Butler (1985) and Reis (1992) are discussed by Azad and Chalaturnyk (A Azad & Chalaturnyk, 2009). A triangular shape of steam chamber was assumed in both theories which predicted a constant rate of oil production and, hence, a cumulative oil which was a linear function of time. Azad and Chalaturnyk (A Azad & Chalaturnyk, 2009) gave the modified version of Reis' model (the Geomechanical Azad Butler, or GAB, model), accounting for heterogeneity in the reservoir permeability. These reservoir models, however, cannot simultaneously represent the full system at all of the appropriate physical scales or complexity. Butler's model, for example, assumes the reservoir to be homogeneous and isotropic without consideration for capillarity because most bitumen reservoirs usually have high permeability leading to small capillary pressure (Ali Azad, 2012). Van Essen et al (van Essen, den Hof, & Jansen, 2013) suggested that significant barriers to successful modelling of production optimization are uncertainty in reservoir response, sub-optimal performance of the reservoir early in its life, and the coarse nature of reservoir models. Several thermal recovery processes, including SAGD, have been modelled using numerical reservoir simulators such as CMG STARS (Computer Modelling Group, 2011)(Carlson, 2006)(Edmunds & Peterson, 2007) and EXOTHERM which allows for detailed analysis of the thermal performance of a reservoir in 3D accounting for the petrophysical properties in the reservoir (Mojarab, Harding, & Maini, 2011).

The next most widely studied domain is on the other side of the completion which involves modelling the multiphase flow within the wellbore. There are several commercially available wellbore models with Flexwell (Shahamiri, Heidari, Buchanan, & Nghiem, 2015), Q-Flow (VanderValk & Yang, 2007) and TWBS (Medina, 2013) being the most prominent. These models are typically based on empirical correlations such as the Beggs-Brill model to predict the behavior the flow (Tan, Butterworth, & Yang, 2002). This approach has been shown to lose accuracy when the flow is at the boundary between two regimes. Other wellbore models, such as the mechanistic model presented by Taubner et al (Taubner et al., 2015) investigate the effect of wellbore hydraulics on production distribution and resulting sub-cool (liquid level) distribution along the wellbore.

STARS, a well known commercial reservoir simulator, employs an element based finite difference method (Rahmati, 2016) to solve for mass continuity, energy balance, multiphase Darcy flow and component mass transport (Zhu, Bergerson, & Gates, 2016). Zhu et al notes that the constiutent equasions used in this software are all linear (Zhu, Wang, Su, & Gates, 2016) and several studies in this area focus on implementing nonlinear physics into the model (Z. Li, Fortenberry, Luo, & Delshad, 2017; Zhu, Wang, et al., 2016).

There has been a great deal of interest in coupling different reservoir level and wellbore models to improve the overall system representation. Vicente et al describes a model which was designed to simultaneously solve reservoir and wellbore domains (Vicente, Sarica, & Ertekin, 2001). Vander Valk and Yang coupled a reservoir model (EXOTHERM) with a wellbore model (Q-FLOW) to explore in greater detail the effects of frictional pressure drop within the completion (VanderValk & Yang, 2007). Rahmati et al described the coupling of FLAC, a geomechanical model, with STARS using Matlab code as the go-between the two software's Application Program Interface (API) (Rahmati, Nouri, Fattahpour, & Trivedi, 2017). Yamada & Furui describe a methodology for bridging the boundary between large-scale and small-scale element based models, a significant issue in SAGD modelling phenomenon (Yamada & Furui, 2018).

Li et al describe the skin model used in STARS in detail, and outline an effort to improve the accuracy of the skin factor to account for non-newtonian behavior of the reservoir fluids (Z. Li et al., 2017). The primary focus of their effort was on the skin factor that can be attributed to convergant radial flow towards the wellbore and modelling the non-newtonian properties of the fluid, but they also mention a more near-field "mechanical skin", which is in effect what the Unified Feature Model presented in this work is attempting to model in detail. Vander Valk and Yang impart a "skin factor" due to flow convergence imparted by the slot density in the completion (VanderValk & Yang, 2007).

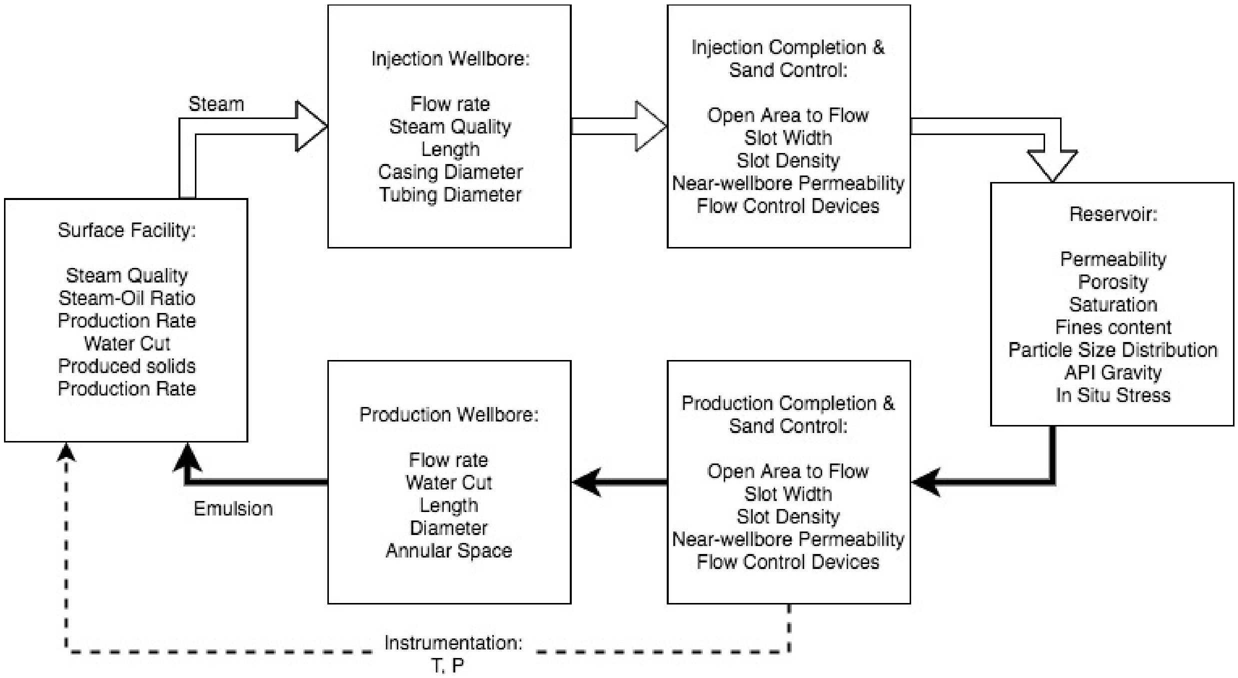


Figure 8: Block Diagram of the SAGD System

### 3.2.3 Advanced Studies of SAGD Phenomena

The most important omission from the previously described domains is an adequate integration of near-wellbore behavior. Numerical simulators require relatively coarse elements, on the order of meters, to capture the behavior of reservoirs with a reasonable computational efficiency. This granularity completely consumes the near-wellbore effects which are relevant at the millimeter and even micrometer scales. These effects, while small in geometric scale, are largely responsible for the degradation of SAGD performance over time, as the flow characteristics at the individual slot level can be directly related to the transport of fines, plugging, corrosion, and scale. Such phenomena are typically the subject of independent investigation by subject matter experts.

The design of sand control devices is of considerable importance as a poor design can have a catastrophic effect on the well due to plugging or undesired sand production. Sand retention models, first explored in the 1930's by Coberly and refined by others ever since, has relied largely on empirical study (Fattahpour et al., 2016). Sand control design models developed by Bennion et al. (Bennion et al., 2009a) and Fermaniuk (Fermaniuk, 2013) were motivated by concerns about the performance of sand control devices, and relied on experimental sand retention tests. Mahmoudi et al. used a multi-slot sand retention test to investigate the effect of slot geometry on pore space plugging (Mahmoudi, Fattahpour, Nouri, & Leitch, 2017). Kaiser et al. (Kaiser et al., 2002) studied the characteristics of the inflow of oil to the production well and the effect of the slot arrangements to optimize the design with respect to slot density and orientation. In their semi-empirical work, they considered the coupling of two types of flows – radial flow through the reservoir to the liner and axial flow through the pipe to the production pump.

The change in the velocity distribution for the flows of Newtonian and non-Newtonian fluids through slots due to the variation of slot geometry was studied by Ansari et al. (Ansari, Rashid, Waghmare, Ma, & Nobes, 2015b). Particle image velocimetry was used to determine the variations of flow at various positions from development of velocity profiles. The results discussed the formation of jets due to variations in slot geometry and shear-thinning properties of the fluids tested.

Flow control devices (FCDs) are installed on the injector well to improve steam placement and chamber growth and improve the long-term productivity of the SAGD process. Li et al. (L. Li, Lange, & Ma, 2015) did a computational fluid dynamics modelling specifically on outflow (Injection) control devices with particular reference to their performance in SAGD operation. A simplified model for the device was used in a series of simulations using commercial software. The control mechanism and flow distribution along with comparison to different flow models were reported.

Zhu et al. attempted to address the gap between the results from very directed scientific studies and field tests through a series of investigations of the effectiveness of an anti-fouling coating (Zhu, Leitch, et al., 2016). Lab results from a series of corrosion and fouling tests were compared to samples recovered from a SAGD well. While this study attempted to address the complexity of the gap between the lab and the field, issues such as the expected rate of fouling of the coating were not presented.

The above studies make up only a sample of works being done in the name of improving the SAGD process. However, these works must be somehow integrated with the commercial reservoir models in order to fully realize the power of these advances. There are two ways whereby these expert systems can be used to enhance established commercial models: enhancing the accuracy of a model by overlaying additional phenomenological considerations; and filling topological gaps between models. In the case of our SAGD system, we hope to accomplish both: (1) enabling the ability to add precision and accuracy to the transformation model (such as adding a scale generation function to the STARS thermal reservoir model, for example); and (2) improving the interface between existing domain models (such as applying a near wellbore simulator in between the reservoir model and wellbore model to improve the near wellbore representation).

### 3.3 Modelling Approaches for Distributed Systems

Recognizing that much of the optimization work in this field is being conducted in a distributed way, i.e. by independent research groups, engineering companies, and consulting firms, cyber-physical methods can be used to help coordinate such efforts (Trappey et al., 2016). The methods employed should be lightweight in order to ensure that their use is not overly cumbersome or resource-intensive to set up and apply, conforming to the requirements of extensibility, interoperability, modularity, and scalability (Zappia, Parlanti, & Paganelli, 2011). Such a system must provide enough structure to allow researchers to effectively coordinate and integrate their work (or prepare it for integration) without surrendering their intellectual property to a centralized integrative authority.

Coupling models from different domains is a common multi-physics approach, and one that is of great interest in the petroleum industry (Swarbrick & Muller, 2016)(Kumar, Oballa, & Card, 2010)(Oballa, Coombe, & Buchanan, 1997). This approach is advantageous where numerical software models are involved because the coupling software can automatically manage runs of each expert system as a black box using an Application Programming Interface (API) to manage the model, without having to access the proprietary code within. The central challenge in the multi-physics approach is managing the complexity and interoperability between different "expert" models (Y.-S. Ma et al., 2006), and ensuring that all of the relevant phenomena are correctly integrated. The challenge in this approach grows exponentially with increasing number of interacting systems. The number of interactions for a web of interconnected systems is $n(n-1)$, where coupling links must be designed between all elements of the system. The notional 'coupling' approach is less straightforward when the models being coordinated are not computer-based, but are rather empirical or experimental in nature. Alternatively, a system where all of the elements are coordinated by a central hub significantly reduces the number of interactions to $2n$. This hub, or semantic model, allows for an extensible framework to enable different "expert" systems to interact (Y. Ma, 2013). Such an integrated semantic modeling approach is adopted throughout this work as conceptually shown in Figure 9 and are reflected in class instances and object diagrams shown later in the following case study sections. Object-oriented data and method sharing is assumed when those semantic diagrams were developed.

### 3.3.1 Feature Modelling

A *feature* can be defined as a representation of an engineering pattern that formalizes the associations between relevant data, using object-oriented software modelling terminology (Sajadfar et al., 2013). For example, in product modelling, a feature can describe a certain aspect of a product's form by reference to the set of information attributes and the associated methods that are used to construct the form. Beyond geometrical attributes, features can encode engineering design intent, and reference other features. When various types of features are associated and combined to form a tree of data structures, they form a feature model. A feature model therefore contains recognizable entities that have specific representations designed to support a specific application purpose as a working system. The number and type of features that are included to form a complete model depends on the function that is intended to be supported, which makes feature models inherently modular and scalable. In general, any part of a process or a product whose change can have the engineering significance to make the system behave in a different way can be called a feature.

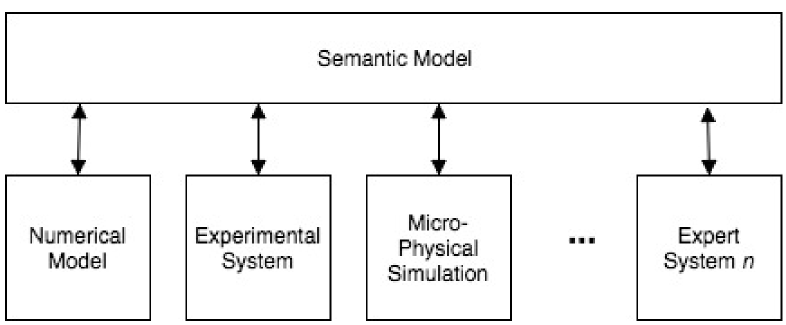


Figure 9: Semantic Modelling Framework

### 3.3.2 Mereological Modelling

Mereo-operandi theory was proposed to take into account the operational and architectural elements of a system (Pourtalebi & Horváth, 2016). Mereology is a philosophical concept which refers to the relations between the whole of something and it's parts, and relations between the parts within a whole. From an architectural perspective, such methods attempt to capture all physical entities of the system. Capturing operational aspects, on the other hand, requires describing the actors along with causes, challenges, and interactions that exist. A recent work by Pourtalebi and Horvath (Pourtalebi & Horváth, 2016), describes how system manifestation features can be used to model complex interactions between the physical and computing components of a system. System manifestation features are defined with semantically meaningful units that represent the architectural and operational aspects into which the system can be decomposed (Horváth & Pourtalebi, 2015).

In mereological modelling, the components that make up cyber-physical systems are assumed to have interactions with all the entities included in the system and not much interface with the external environment. To develop the component or the system model with respect to the operational aspects, a non-exhaustive rather than an exhaustive description of the operations is also deemed sufficient. The domain of empirically observable architectural relationships and physical operations has to be identified along with their respective attributes. The interactions between and within each domain can then be established through an identified relationship between morphological attributes and the physical components that describe the systems architecture (e.g. geometry). The final output from such a modelling approach can be the sequential flow of operations of the system for the desired function (Horváth & Pourtalebi, 2015).

### 3.3.3 Research Objects to Manage Workflow

Managing workflow and ensuring the dependency of expert areas engaged in design projects of significant complexity can be challenging. It has to be ensured that the flow of data between expert areas follows the required dependencies and other sharing policies. Systems that are built based on the concept of Research Objects are emerging with the aim of preserving scientific workflow alongside traditional publications (Belhajjame et al., 2015). The tools that already exist provide the capacity of sharing, and aggregation of a research activity in its entirety. The management of research and design works that involve considerable collaboration and concurrency will undoubtedly benefit from such data sharing systems.

### 3.3.4 Phenomenon Features

Integrating on the above concepts, the Phenomenon Feature Model is proposed to conceptually model and coordinate the various phenomena and expert systems used to describe complex engineering processes. For a process that is being modelled as the combination of disciplinary phenomena, informatics modelling allows a framework of multiple tiers where we can find one within, or related to, the other. Parameters, attributes, constraints of each domain as well as their behaviors can be represented in the computer interpretable data structures, i.e. phenomenon features, via object-oriented software engineering approach. Each can be considered as an instance, or the child class, of a generic phenomenon feature type. A class definition that can be used to describe all of them regardless of their instance attribute values and application tiers is thus needed for a successful modelling of complex engineering system where parent-child relationships can be utilized.

Using the feature modelling approach, independent models which describe different physical phenomena can be brought together to describe the full system in a coordinated and comprehensive fashion. In this way, the system model can be easily expanded to include new phenomena as those models are developed by researchers, updated with more mature models as they become available, or easily reconfigured if it is suspected that competing phenomenon models could improve the overall result. The concept of associative features, which enables the design of dynamic systems based on feature relationships, is proposed for this purpose (Y.-S. Ma & Tong, 2003).

### 3.4 Development of a SAGD Production Tooling Semantic Model

In view of the modelling and informatics concepts discussed above, it can be seen that there is an opportunity to consider an engineering design problem of significant complexity. It is shown in this paper that the different phenomena involved in SAGD can be treated as features, using associations to relate the components to each other and enable the application of feature-based modelling techniques to describe their interaction. The very first step is to develop the semantics model. Both physical and software systems can be mapped in such a model. Next, the different expert areas that are part of a complex design process of SAGD tooling system can be identified and their characteristic properties, related constraints and functions (i.e. *features*) in system engineering are represented in a unified mark-up language. Then, their relationship determined in a consistent and complete way that allows for interdisciplinary knowledge engineering, expertise management, communication, and further future software system interoperability. Most importantly, a collaborative information system can be put in place to coordinate the efforts of developing engineering modules or components systematically, whether it be a computer model, numerical simulator, experimental system, or team of human beings. Finally, it can be expected that in future system implementation, initial conditions are to be applied, assumptions simplified, order of operations are instantiated and managed, interfaces and modes of collaborations developed, and further system design changes managed. This section outlines the major steps which are taken to approach the development of the SAGD production tooling semantic model.

### 3.5 Functional Decomposition of the Expert Engineering Domain

It is often possible to decompose complex phenomenon into a collection of expert domains for the purposes of building the framework for the semantic model. It is helpful to begin the decomposition process using a high level mathematical relationship as the basis. Oil production within the SAGD process technology is a combined transport phenomenon itself for which several aspects of the principal conditions have to be fulfilled, e.g. heat and mass transfer, and multiphase flow through porous media. Production rate, which is perhaps the most significant measure of SAGD production, can be predicted and optimized using a model for oil production. Reservoir properties, temperature and pressure distributions, fluid properties, and the flow regimes and schemes will result in the parameters that can be used to solve the conservation and governing equations which define the system.

The SAGD process, like all oil sands extraction processes, relies heavily on Darcy's law, which describes the flow through porous media. According to Darcy, the reduction in pressure, $P$, across a porous medium of depth, $L$, is proportional to intrinsic properties of the porous medium and the fluid (permeability,$\kappa$, and viscosity, $\mu$, respectively) and the cross sectional area, $A$. The relation is given as:

$$Q = -A\frac{\kappa}{\mu}\frac{\Delta P}{L} \tag{1}$$

where $Q$ is the total discharge.

Butler's theory for production rate of heavy oil and bitumen combined the heat conduction theory with Darcy's law (Butler, 1994)(Bao, 2012)(Ali Azad, 2012). The resulted equation from his theory to predict the production rate was:

$$Q = \sqrt{\frac{2\phi \Delta S_0 \kappa g \alpha h_f}{m \nu_s}} \tag{2}$$

where $Q$ is oil production rate; $\kappa$ is permeability; $\alpha$ is reservoir thermal diffusivity; $\varphi$ is porosity; $\Delta S_0$ is the difference between the initial oil saturation and residual oil saturation; $h$ is the height of model; $m$ is a dimensionless factor which is dependent on the oil viscosity-temperature relationship; and $\nu_s$ is the kinematic viscosity of the oil.

As the oil drains towards the wellbore, it converges radially towards the wellbore. At this point the integration of Darcy's law gives:

$$Q = \frac{2\pi\kappa h}{\mu} \frac{\Delta P}{\ln \frac{r}{r_w}} \tag{3}$$

where $\Delta P$ is the pressure change between the reservoir and wellbore, and $r_w$ is the wellbore radius (Matanovic, Cikes, & Moslavac, 2012).

In order to explain deviations between this theoretical model and reality, van Everdingen and Hurst developed the concept of skin factor, $S$, which lumps all of the near-wellbore phenomenon into a single factor which can be measured (van Everdingen, 1953). Adding this skin factor term into Equation (3):

$$Q = \frac{2\pi\kappa h}{\mu} \frac{\Delta P}{\ln \frac{r}{r_w} + S} \tag{4}$$

This generic skin factor can be decomposed into components:

$$S = S_1 + S_2 + S_3 + \cdots + S_n \tag{5}$$

where each component represents the contribution of a particular phenomenon to the overall skin factor.

Datta and Bhuyan broke $S$ into several factors including: skin obtained from flow test; skin due to formation damage by drilling mud; and skin due to non-Darcy flow (Datta & Bhuyan, 1980). Ohen and Civan discuss skin damage due to fines migration and clay swelling (Ohen & Civan, 1991). This concept can easily be expanded to include any phenomenon which adds resistance to flow in the reservoir. Sand control, localized flow convergence, and sand control plugging, for example, have all been shown to influence the overall pressure drop, and therefore productivity, of SAGD wells (Romanova & Ma, 2013)(Kaiser et al., 2002).

In reality, the contributions of each phenomena to the overall skin factor is rarely constant with time or reservoir properties, and many are dependent on each other. Using feature modelling concepts, we can begin to understand the relationships between the contributing factors to skin, and integrate expert models that are capable of predicting the phenomena behavior into a unified model that can better describe the whole system.

Therefore, the major contribution of the feature model in this industrial case can be identified as: defining the relationships and dependencies between contributors to skin; using those relationships to identify the order of operations and expected iterations required during the execution of the design model; identifying and consolidating simplifying assumptions among model elements; defining the set of initial conditions (IC's) which should be considered by each element; identifying where model elements are tightly coupled, requiring active collaboration between expert areas to resolve efficiently.

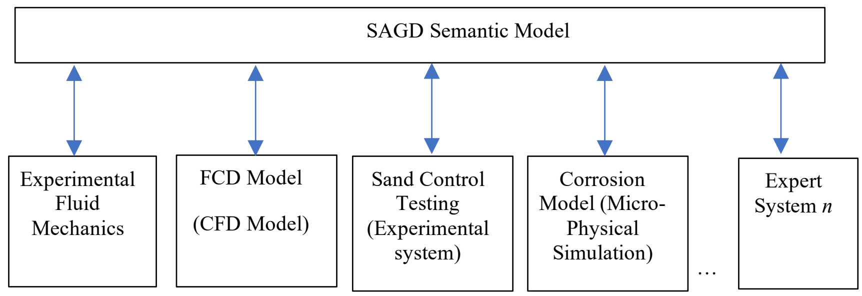


Figure 10: SAGD Semantic Modelling Framework

For the purposes of this paper, we have chosen four expert domains which are actively being studied by associated research groups at the University of Alberta as a focal point to demonstrate our integrative efforts. These are, a computational fluid dynamics model of flow control devices (Carlos Lange, PI) (L. Li et al., 2015); experimental investigation to identify the effect of flow on failure mechanisms of slots (David Nobes, PI) (Ansari et al., 2015b); an experimental sand control testing system (Alireza Nouri, PI) (Mahmoudi et al., 2017); and a corrosion model (Jingli Luo, PI) (H. Luo et al., 2015). We will not explore each of these expert areas in great depth, as it is not necessary to understand each expert area in great detail. Rather, our focus is on defining the relationship between these expert systems and the semantic model under development is structured with the semantic model as the hub in the "wagon wheel" approach as previously described, and illustrated in Figure 10.

### 3.6 Phenomenon Feature Definitions

Laying out the conceptual models for SAGD features, this work defines a new generic feature type whose interactions can be demonstrated using the SAGD lifecycle processes as a template. The definition of a *phenomenon feature* is depicted in Figure 11. Elements/components, conditions, and presumptions can be used to describe a *phenomenon*. The underlying principles for its behavior can come from general governing equations, and process constraints. The behaviors of the phenomenon can then be applied to solve the governing equations, to model its functions, and to predict and/or optimize its outputs.

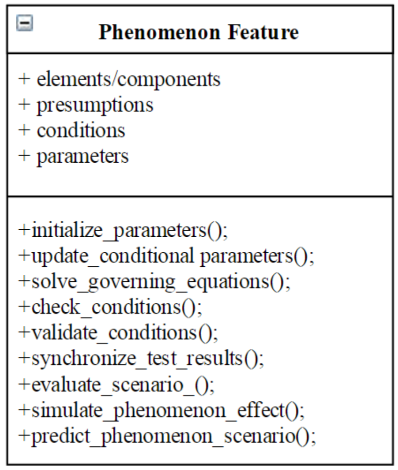


Figure 11: Definition of a *Phenomenon Feature*

Based on the concept of disciplinary principal phenomenon features described and significant components identified, four child *classes* of phenomenon feature *oil production* shown in Figure 12 were constructed with their respective and relevant attributes and methods. The physics of the flow and heat transfer phenomena that take place in the SAGD system were the obvious foundations behind the construction of these *sub-classes*. The methods within each *sub-class* are either well defined or the subject of current research, in which case reasonable models exist to approximate their behavior. Nonetheless, the modular nature of the object-oriented approach allows for refinements to each *sub-class*, which represents an expert area in itself. To complete the model and meet the objectives, further inclusion for the design and manufacturing of well tooling components of a SAGD system was required.

### 3.7 Unified Model

The process of SAGD can be represented as a set of phenomenon features. However, in order to capture the full complexity of the system a layered or tiered approach can be invoked, a common approach in data modelling (West, 1996). The associations between features must be carefully defined in order to accurately represent dependencies during an analysis of the model. The set of initialization methods of object attributes related to object initial conditions may also be defined at this point.

Based on the definition given in the above section, the entire SAGD phenomenon forms the top-most tier and the related phenomena can be expected to make up the lower levels; the simplest representation is shown in Figure 13. The top layer form the core conceptual level of the model, and are designed to interact with external expert modules, which invoke the various expert systems which model the specific phenomena.

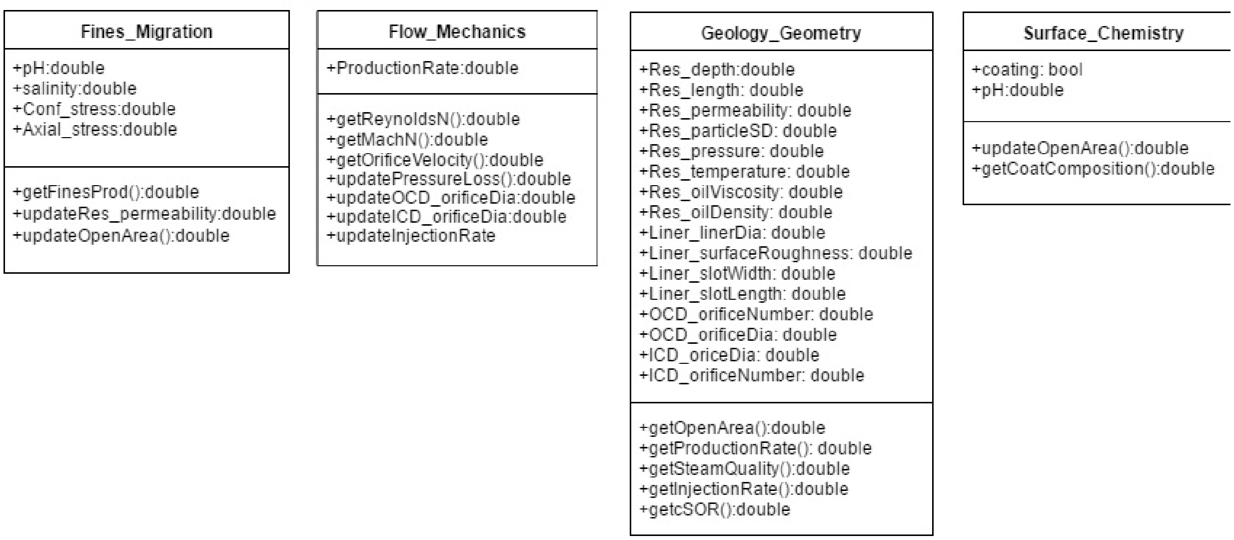


Figure 12: Defined *Classes* of Phenomenon Features for SAGD Simulation

As we move from the phenomenon model to the design model, we must use the same approach to define the components which will interface with the phenomenon. The product specification is implemented to serve the purposes of flow control, sand control, ensuring strength and stability of the well bore. For a specific completion method there are corresponding conditions that need to be maintained within the reservoir and the wells to attain acceptable levels of pressure and flow control performance under the working temperatures.

The relationships between the *classes* shown in Figure 12 were established based on the dependencies and aggregation of attributes and/or output parameter(s) (shown in respective methods' section). Such modules make up the final model for the integrated system of SAGD process, but as new phenomenon are considered, additional *classes* may be easily implemented in order to further refine the resulting design model.

## 3.8 Discussion

### 3.8.1 Work Completed to Date

This methodology has been deployed in a multidisciplinary research group at the University of Alberta, Canada. The research teams are fully independent, and due to their deep subject specialties their activities are not always semantically consistent. The challenge of coordinating the works of these different groups was what inspired the model described in this paper.

A computational fluid dynamics (CFD) model of the flow interactions between flow control devices requires careful consideration of the temperature, pressure, and geological conditions along the entire wellbore (L. Li et al., 2015). That geological condition is highly dependent on the sand control performance, which has not been adequately modelled digitally. Common practice in this instance is to use experimental sand retention tests in order to evaluate the effect of sand control devices on the fines migration and plugging of the near wellbore space (Fattahpour et al., 2016). Corrosion has been identified as a serious problem, and new coatings are being evaluated in order to improve the performance of the sand control device. Obviously the pressure, temperature, and composition of environmental fluids plays a significant role in this phenomenon (H. Luo et al., 2015). If improving the geometry of the slots on the well completion is to be sought, it should be proceeded by developing an understanding of the fluid mechanic consequences. An experimental investigation to identify the effect of such slot geometry (the aspect ratio) is underway to come up with a mathematical description of its effect on the pressure loss (Yusuf et al., 2017).

By coordinating these expert areas through a central hub, as different hypotheses are tested and new sensitivities are identified the requirements and constraints of the associated models can be actively updated. For example, pH and salinity were recently shown to play a great role in near wellbore plugging tendencies (Mahmoudi, Fattahpour, Nouri, & Leitch, 2016), which is an important consideration for other nodes in the system.

One goal of this study was to develop a method which conforms to the requirements of lightweight systems if it is to be used by anybody, so the model will now be discussed through the lens of each of those requirements.

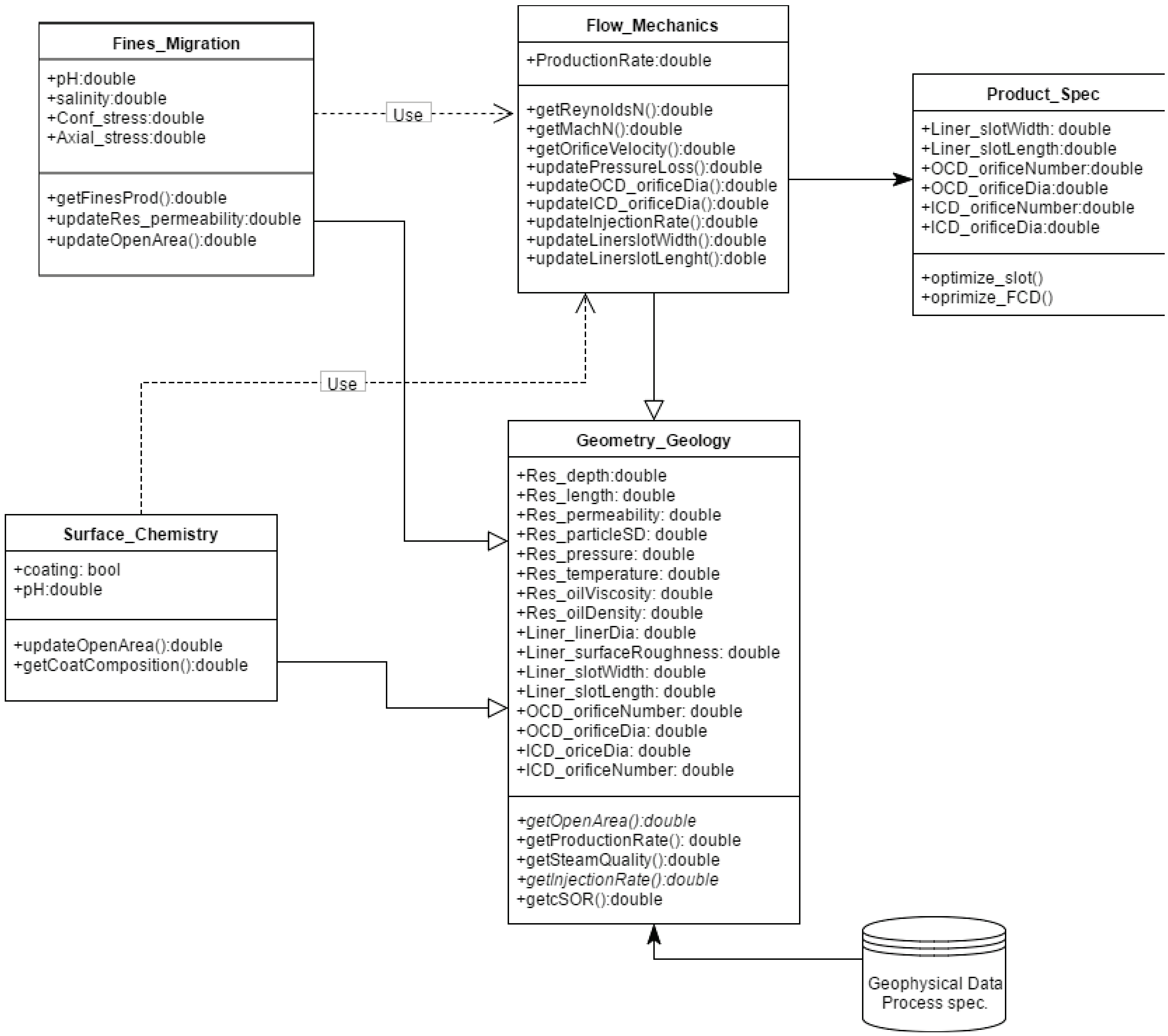


Figure 13: Semantic Model Framework for Complex SAGD Production Tooling System

### 3.8.2 Interoperability

Interoperability has been a major challenge since the emergence of computer aided engineering (Y. Ma, 2013). In multi-physical processes, it is obvious that the interoperability between expert systems is advantageous, and this issue was a main motivator for this study. In the defined system, interoperability is achieved through the inheritance and association mechanisms available to us using the object-oriented approach. By recognizing the overlap between expert areas in the structure of the system, each expert system is automatically associated with other expert systems which share inputs and/or outputs.

The idea is not necessarily to hard-code the expert systems together. This might be plausible in some cases, but in cases where physical/experimental systems interface with cyber-systems, for example, hard coding is not practical. However, by defining the relationships, experts can conduct their work with a full understanding of other activities in the system that can control/affect their inputs, and likewise, how their activity can control/affect others. Whether automated via code or not, the system facilitates the communication of rich engineering ideas that allow for effective collaboration, even in distributed communities. Figure 14 shows the pathways that enables integration of geological data and geometrical estimates into three functional evaluation modules, i.e. *Flow Mechanics*, *Fines Migration*, and *Surface Chemistry*.

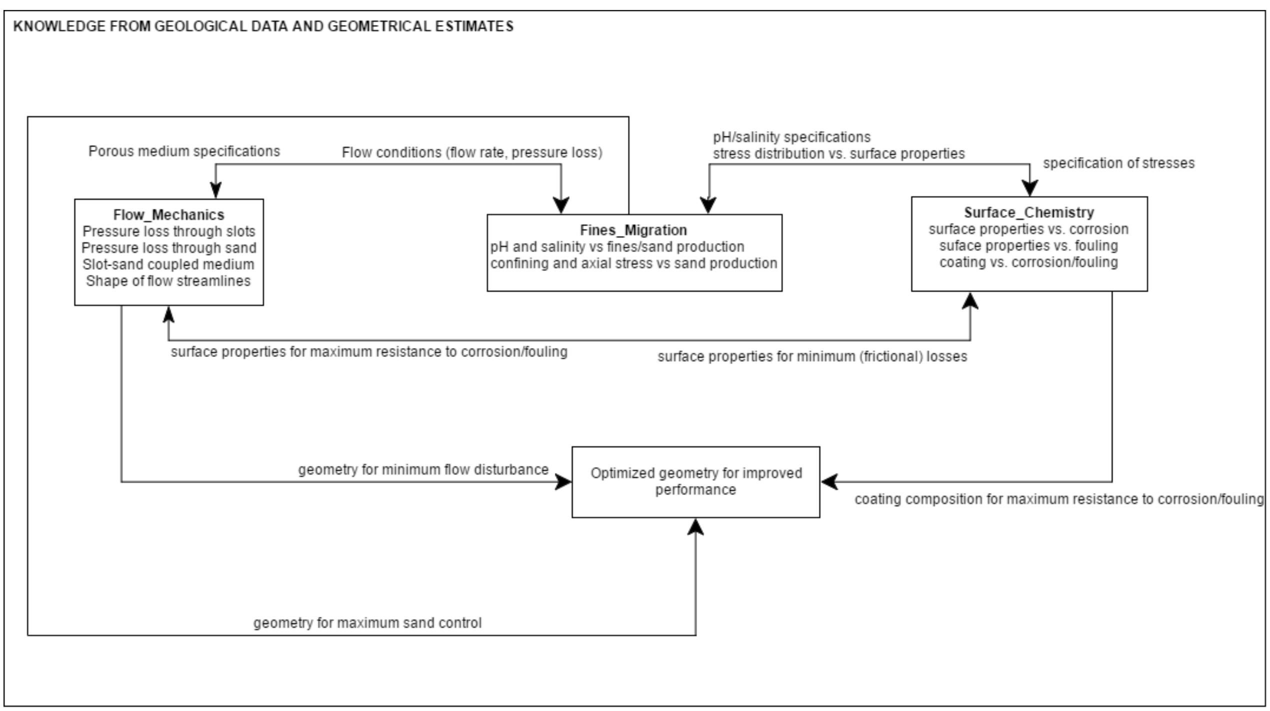


Figure 14: Object Diagram Showing Pathways

### 3.8.3 Extensibility, Modularity, and Scalability

The presented framework is extensible, thanks to the object-oriented approach. It can easily accommodate additional functionality as required, whether it is the accommodation of new phenomena or new expert systems.

The class structure, which is fundamentally modular in nature, allows for the addition of new classes with similar levels of abstraction. This modularity also accommodates the needs of distributed engineering systems that must be able to operate independently within their own expert domain.

In order to scale the system up (or down), one needs to only instantiate a new set of phenomenon objects. The scale of the system is only limited by the scale of the expert systems which are contributing to it. This system is well suited for repeatability: There are tens of thousands of SAGD wells currently producing, and hundreds more are planned for the coming year alone. From the authors' industrial practice observation, majority of these SAGD well production systems are not optimized with a consistent optimization model and yet localized reservoir conditions. This propose expert system allows for the efficient deployment of well-coordinated systems in order to properly configure as many wells as are required.

### 3.8.4 Change Management

A major opportunity that has emerged with this technology is the ability to formally track changes in the engineering system, as well as properly anticipate the effects of changes in different systems. Because the system keeps track of the dependencies and interactions between system elements, independent experts in the distributed system can instantly appreciate how changes in their domain affect the broader system in the context of the other expert areas.

### 3.8.5 Iteration Management

The single biggest opportunity that this framework provides is the ability to manage the order of operations and concurrency within complex systems to manage the expensive iteration process. The dependencies that are identified in the knowledge model allow system actors to identify whether processes are: tightly coupled, guaranteeing iterations; loosely coupled, with a risk of iteration; or uncoupled, where there is no risk of iteration during concurrent execution. Where the processes are tightly or loosely coupled, the sensitivity of the various systems can be measured and the risk of iteration can be calculated.

## 3.9 Conclusion

This paper presents a CPS model to provide a framework for integrating expert systems found in the various engineering domains of the SAGD oil extraction process. Major phenomena that occur in the reservoir that are known to affect the system performance are coordinated in order to facilitate multi-disciplinary optimization of the system.

Object-oriented unified feature modelling approach was employed to identify the components of the model and establish their relationship. The reason for selecting this approach is foreseeing the suitable application of the concept of associative features in the expansion of the model.

The model is lightweight, which means it is extensible, scalable, modular, and provides a framework to ensure interoperability between expert systems. Unlike most knowledge management and project management schemes, the proposed framework does not require centralized project management or control. It is easily deployed across a distributed engineering system consisting of independent work units operating in separate expert domains.

The model has been implemented in a distributed research group studying various aspects of production efficiency in the steam assisted gravity drainage oil production process. It has been shown that the phenomena which contribute to the system's performance can be modelled and related to each other in such a way that the various expert systems can communicate and coordinate their activities, while minimizing the risk of expensive iterations.

The system described is undergoing active development. Following phases include the formal integration of several different phenomena which are known to be tightly coupled; then the development of (the prototype for) some computer system/interfaces shall follow. Based on the proposed semantics model that is created, analytics modules are planned to assist the teams in coordinating the order of operations of their work in order to minimize the use of oversimplified assumptions and minimize the need for development iterations.

# 4 Detailed Feature Models to Define and Coordinate Expert Systems

The previous chapter oulines the functional decomposition of the SAGD system, defines the scope of several expert domains at a conceptual level, and defines classes of *phenomenon features* whch represent the service environment's interactions with the SAGD system. In order to design an effective SAGD completion we have to understand:

1) How do the phenomenon features map onto the design schema?
2) How can engineering design tools be used to model the interactions and optimize the system's design?
3) How best to coordinate the engineering design activities to maintain quality while minimizing cost?

## 4.1 Structuring the Information Modelling Infrastructure

As described by Sajadfar et al, semantic repositories can be structured as different layers of granularity and fuction (Sajadfar et al., 2013). Semantic modelling literature tends to break the information modelling infrastructure into layers and sub-layers. Ma et al modelled these four layers as shown in Figure 15 (Y. Ma et al., 2008). In our case, the set of defined Phenomenon Features can be considered as living in the "Knowledge Based Semantic Module", which encapsulates expert knowledge about the interaction of the system with the service environment. However, the methods required for complete representation of this phenomena are too complex to be instantiated as a single object. Therefore, in order to allow for flexible continuous development and integration of new models, experiments, and simulations, the "Application Feature Module" is used to house representations of the expert systems which will provide the functionality that the Phenomenon Feature's methods require. The "Unified Feature Module" contains the semantic design representation that models the physical system. The Geometric model is the design model which is ultimately generated from the design effort.

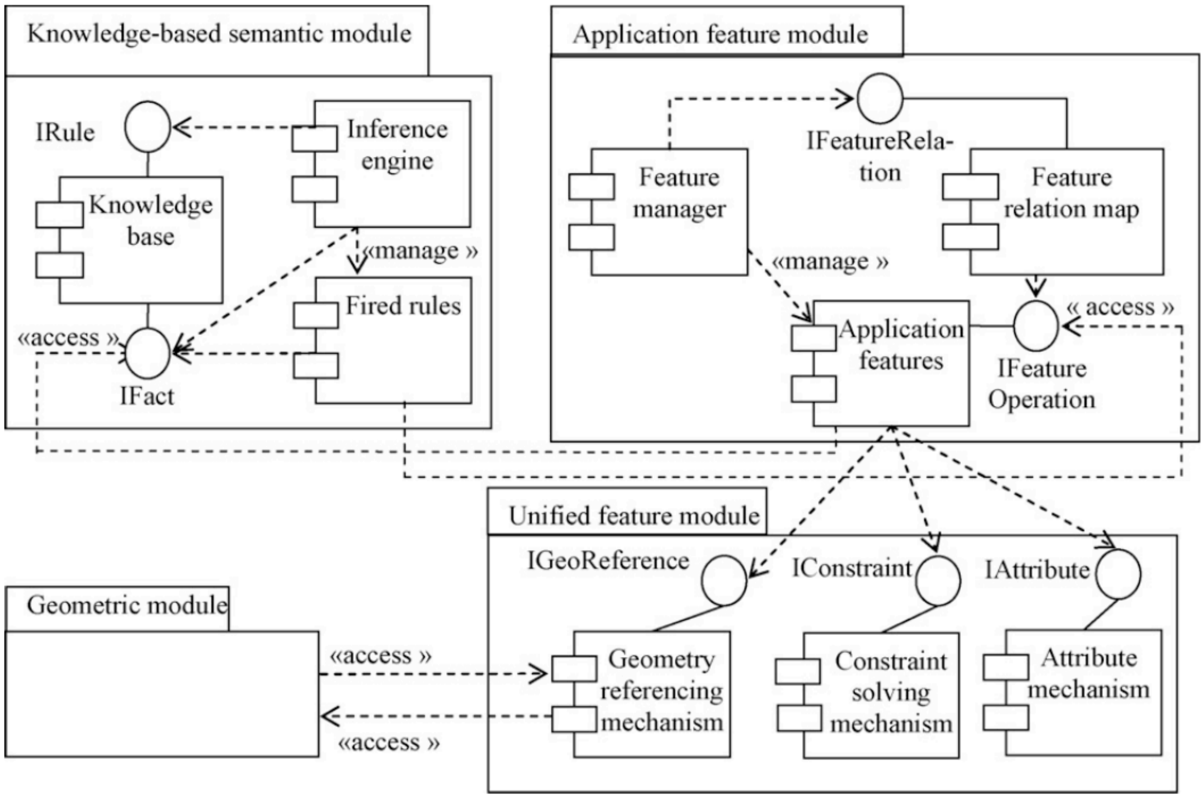


Figure 15: Intra-stage associations in the Unified Modelling Scheme. From (Y. Ma et al., 2008)

In the following section we will define the Unified Feature Design Model which represents the physical representation of the SAGD system. This semantic model will ultimately drive a parametric design model which could be represented in 2D or 3D CAD, or autonomously generated design specification documents used to manufacture and assemble the parts of the system.

The Phenomenon features which populate the Application Feature Module were defined in section 3.6. These features, when instantiated, must be able to call upon (potentially several) knowledge-based expert systems to determine the parameters required by the phenomenon model. These knowledge-based semantic models represent engineering design tools used to help in the design of an optimized system. They will be designed to fulfil the requirements of the methods (functions) defined in each of the Phenomenon Features. Due to the generic nature of the semantic modelling technique we can use the same methods to model both software and hardware based expert engineering systems (ie CAx software & testing apparatus).

## 4.2 SAGD Reservoir Unified Feature Design Model

The Design model follows the SAGD Block diagram presented in Figure 8, and is presented using UML and following the generic feature conventions presented by Tang et al. (Tang et al., 2013). The class diagram structure, shown in Figure 16 is completed with relationships and parameter sets that are commonly used in the design, manufacture, and operation of SAGD systems. The methods block of each class specifically calls out the Phenomenon Features defined in the previous chapter.

## 4.3 Corrosion Domain

### 4.3.1 Defining the Corrosion Phenomenon

The combination of high temperatures, pressures, and chemical environments which include CO2, H2S, water, and a complex mixture of hydrocarbons and minerals present an extremely corrosive environment for steel parts. A study by the National Association of Corrosion Engineers (NACE) pegged the cost of corrosion in the Oil & Gas Expolration and Prodution sector at $1.4B/year, with $500m/year attributed to downhole tubing corrosion (Gerhardus H. Koch & Brongers, 2002). Corrosion is an insideous problem due to the contrasting properties of the products of corrosion and base material: The products of steel corrosion have a greater volume than the base material, lower density, lower strength, and unfavorable surface properties which act as deposition sites for organic and inorganic foulants such as clay, fine sand, and precipitates.

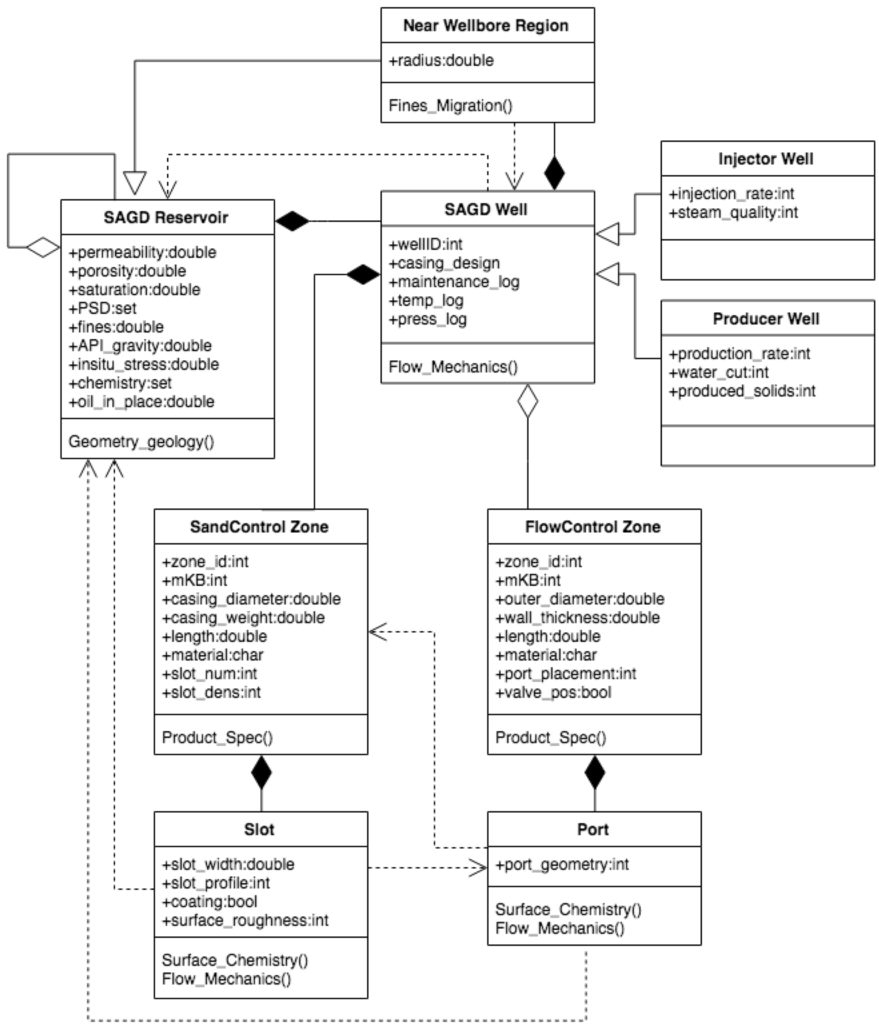


Figure 16: Relations among SAGD design elements

In downhole systems, the options for mitigating issues caused by corrosion are unfortunately limited: Chemical treatments are available which have been shown to correct degredations in performance (at least temporarily) by dissolving and washing away clay and scale whose deposition may be enhanced by corrosion (Frenier & Ziauddin, 2010). Damage caused by corrosion is impossible to reverse without replacing the damaged parts. On wells completed with tubing strings, damaged tools can be pulled and replaced. When it comes to damaged casing and sand control completions, however, pulling and re-running new completion is usually not an option, and a new well will instead be drilled and completed.

Corrosion contributes to three significant modes of failure of downhole systems: Mechanical failure, leakage, and fouling (plugging).

Mechanical failure is caused by the corrosive degredation of the cross-sectional area of structural elements. Eventually, the load on the structure will exceed the remaining structural material, and the structure will fail.

Leakage is often attributed to flow paths being created by corrosion, whether it be holes through the sidewall of a pipe or pressure vessel, or the compromising of the seal between system elements, such as a failure in the bond between cement and casing, creating flow path through a threaded connection, or between tight fitting elements such as the sealing ring in a packer tool.`

Much of the published literature on corrosion problems in downhole systems focusses on mechanical failures and leaks, likely because these failure modes are more acute, and fixing such events require significant amounts of money and manpower. The root causes of fouling, gradually effecting system performance & efficiency over longer periods of time, are often difficult to discern based on performance data alone. In an analysis of plugged slotted liner pulled from a SAGD well in the MacMurray formation in northern Canada, Romanova et al. documented significant amounts of iron oxide and iron sulphide, but also significant amounts of clay fines, and quartz. They describe the deposition of the fouling material as "films of the plugging material consisting of predominantly corrosion products and clay, gradually choking slots" (Romanova & Ma, 2013).

Mitigating fouling in downhole operations is neither easy nor cheap. One of the issues is that mitigation options are limited. Typically the system is flushed with acid in an attempt to dissolve scale, oxides, and disperse accumulated clay. These "acid jobs" typically require at least 2 days of inturrupted production to cool the well, circulate acid, flush the acid to surface, and reheat the well to operational temperatures (the energy costs are non-trivial). Such an intervention has shown to improve production rates in the short term, but the long term effect of these acids on the downhole system is unknown. Cenovus' Foster Creek SAGD facility, for example, reported the disposal of 825m^3 of HCL in 2015 as a result of their acid workover program, which maintains 19,358 m^3/day of oil production with ~243 active producer wells. The reason they cite for the workover program is to "minimize skin" (Cenovus, 2016).

Corrosion rates may be amplified by other conditions synergistically. A common example of synergistic corrosion is corrosion in flow containing abrasive media, which can lead to erosion-corrosion. In this case, the factors of corrosion can be said not only to be chemical, but also mechanical in nature: The relative hardness of the substrate and slurry particles, the velocity of the travelling particles and the impingement angle of the particles all play an effect on the corrosion behavior of a material (Mohammadi & Luo, 2011).

From an design engineering perspective, three aspects drive the system's performance with regards to the corrosion phenomena. The first is a defition of the causes which drive the corrosion phenomena (ie. The system material and service environment); The second is a model for the effects or consequences of the corrosion as a function of time; The third is the response of the corrosion phenomena to dynamic conditions such as the flow of charged and erosive particles at the surface, or phase changes of the fluid (as is the case with steam flashing).

### 4.3.2 Detailed Corrosion Pheonmeon Feature

The Phenomenon Features defined in chapter 3 called for a number of methods relating to corrosion:

```
+getCoatComposition()
+updateOpenArea()
```

getCoatComposition() refers to the the surface of the steel part, as the surface characteristics of the part have such a great influence on corrosion performance. The service conditions should dictate whether or not a coating or special alloy is required, and if so, with what properties.

updateOpenArea() refers to the tendency for corrosion to cause the erosion/degredation of base material (which would increase the open area of slots), while also providing nucleation sites for foulants such as clay and scale, which have been shown to significantly decrease the open area to flow.

The processes used to evaluate the functional methods required for the Corrosion Phenomenon Feature are experimental, at the moment, and can be grouped in to distinct suites of laboratory tests: Corrosion evaluation and Fouling evaluation. The features defined in Figure 17 represent these experimental evaluation programs, and map directly onto physical tasks that are performed as part of the SAGD design process. The experimental methods described below may be considered instantiations of the Evaluation Features.

Corrosion is described using an electrical circuit model, using the impedence of the system to represent resistance to corrosion. System impedence is measured experimentally using Electrochemical Impedence Spectrosocpy (EIS) (H. Luo, Leitch, Zeng, & Luo, 2018). The

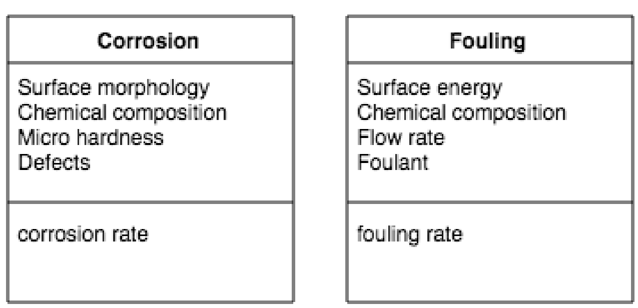


Figure 17: Corrosion Evaluation Features

corrosion measurement apparatus consists of a vessel in which the operating conditions are simulated, a material specimen to be tested, and three electrodes: the working electrode is connected to the specimen, while a counterelectrode and reference electrode are in contact with the simulated environment. A potentiostat/galvanostat and frequency response analyzer is used to provide a polarization curve, which measures the current density as a function of potential. The slope of this curve can be used to derive a corrosion rate, measured in mm/year (X. Chen, 2016). Standard EIS experiments provide data on the bulk performance of the specimen view of the specimen performance. For a more detailed view scanning electrochemical microscopy (SECM) can be used to probe surface reactivity with great precision. SECM techniques can be used to examine the nature of corrosion at discontinuities in a coating, such as in an area which has been mechanically compromised, as compared to corrosion on a specimen which is evenly and uniformly coated (J. Wang et al., 2017). Corrosion is also characterized by examining the physical and chemical products of corrosion, using Scanning Electron Microscopy (SEM), Energy Dispersive X-Ray Spectroscopy (EDX), and X-Ray diffraction (XRD). The morphology of a coating, for example, described by both the grain structure and compactness of the coating, is known to be a variable which effects the rate of corrosion (Q. Y. Wang et al., 2017). These activities collectively provide the data needed by the Corrosion Evaluation Feature and Corrosion Phenomenon Feature.

Fouling is caused by the adhesion of foulants to the aperture surface. Atomic Force Microscopy (AFM) is used to measure the forces (on the nano-newton scale) of attraction and repulsion between the substrate material (steel or coated steel) and the fouling material, which can include organic particles such as asphaltene or paraffin, or inorganic particles such as silicon oxide, clay, or carbonate scale (Lu, Huang, Maan, Liu, & Zeng, 2018). Bulk fouling tests and Quartz Crystal Microbalance (QCM) tests allow for the study of deposition of materials in static and pseudo-static environments and observe how the rate of deposition changes with time (Ji, 2013). The objective is to quantify and understand the reasons why particular coatings have desirable or undesirable effects on the fouling process, and modify coatings and slot geometry accordingly. As with the corrosion evaluation feature, analytical equipment such as SEM, XRD and EDS, can be used to characterize and quantify the materials present on the surfaces of recovered liner and produced solids.

## 4.4 Fluid Mechanics Domain

### 4.4.1 Defining the Fluid Mechanics Phenomenon

There are four flow scenarios in the complete SAGD production system: Flow through porous media (far field), flow through porous media in the near-wellbore region (near field), flow through sand control apertures, and open-channel flow inside the completion. Flow through the porous media in the far field has been well represented mathematically, empirically, and with simulations (for example, STARS (Computer Modelling Group, 2011)). Approaching the design of a downhole system, we will focus on the scenarios which are directly affected by our design decisions: The near-wellbore flow has been shown to be directly influenced by the design of sand control device (Fermaniuk, 2013; Kaiser et al., 2002), and the flow through the sand control device is obviously tightly coupled to the geometry of the apertures and the characteristics of the fluid and flow field (Ansari, 2016). The open channel flow inside the completion can be quite complex, with axial pipe flow interacting with impinging flow from slots and flow control ports or nozzles (L. Li, Lange, & Ma, 2016).

The various flow fields in the SAGD downhole system include a broad range of flow domains, which is characterized by the Reynolds number and Mach number (L. Li, Lange, & Ma, 2018). Rasimarzabadi et al describe the extremely low flow rates that can be found in a nominal sand control aperture (Rasimarzabadi, Leitch, Ansari, & Nobes, 2016). This case study described a nominal SAGD horizontal producer with 1000m of 7” slotted liner with an open area of 1-12%, and calculates the flow rate through a single slot, assuming normalized flow along the producer’s length. This results in flow rates through each slot of 0.17-1.77 mL/hr/mm2 of open area. The resulting reynolds numbers of 0.05-0.5 characterize the flow as “creep flow”, where viscous forces cannot be neglected. On the other end of the spectrum, the flow of steam in SAGD systems can have extremely high reynolds numbers, characterized as turbulent flow. Li et al (L. Li et al., 2016) describe the challenges in modelling the flow in such a geometrically complex system, and expand on this work where they use artificial intelligence to autonomously implement appropriate turbulence models in their simulation (L. Li, Lange, & Ma, 2018).

Another challenge in defining the flow domain concerns the physical characteristics of the fluids (and mixtures) found in the SAGD system which include fluid density and viscosity (rheology), localized velocities, sand fragment size and shape, and well inclination (Matanovic et al., 2012). During steam injection, steam of varying quality is injected through the tool string and out of the slots in the sand control device to heat the reservoir and lower the viscosity of the bitumen. During production, the bitumen (oil) and hot water, which includes both the condensate from steam injection and the connate water found in the reservoir, is produced. This two phase flow may contain two distinct phases, but under certain conditions it may emulsify (Azom, 2013). The flow field may also contain solid particles: fine silica, clay, products of scale, and products of corrosion. In some cases a third (gas) phase may be present, as steam breakthrough, steam flashing, or natural gas production (Bennion, Gupta, Gittins, & Hollies, 2009b).

Flow through porous media is usually described using Darcy’s law, which was developed empirically by Henry Darcy in 1856 to describe single phase flow through a fully saturated porous medium. It has since been expanded and refined to accommodate more complex flow scenarios with greater accuracy (Muccino, Gray, & Ferrand, 1998). The concepts of porosity, permeability, and in the case of multiphase flow, relative permeability, allow engineers to accurately model the relationship between flow rate and pressure drop. A commonly used expression of Darcy's law is shown in equation (6). The elegance and simplicty of the expression can be attributed to all of the system's complexity being bundled in the permeability factor $\kappa$, which for most cases must be determined empirically. Common practice in well design is to send core samples for permeability analysis, and combine with geological data to generate permeability maps for the whole reservoir (See (*Suncor MacKay River Project 2016 AER Performance Presentation*, 2016) for examples of how this data is expressed). In heavy oil extraction, where there is always at least two phases (oil and water), relative permeability is used to describe the variation of permeability as a function of saturation. W refers to the "wetting phase", which is the fluid phase which surrounds the grains in the porous media, while n refers to the "nonwetting phase", which is the phase which fills the voids between grains.

$$Q = -A\frac{\kappa\kappa_r^{\alpha}}{\mu}\frac{\Delta P}{L} \qquad \text{where } \alpha = \mathrm{w}, \mathrm{n} \tag{6}$$

Reservoirs may be referred to as "water-wet" or "oil-wet", which can change the expected productivity of a reservoir dramatically, as well as the strategy for exploitation (Crowell, Bennion, Energy, Thomas, & Bennion, 1991).

Permeability is most commonly described as a function of saturation, but it is also sensitive to a number of other factors. Muccino et al describes viscous coupling, which essentially describes the transfer of momentum of one phase on the other through the phase interface (Muccino et al., 1998) . Other effects may include changes to the permeability due to the mobilization and/or deposition of fines or scale, and the swelling of clays. This can be caused by a number of factors

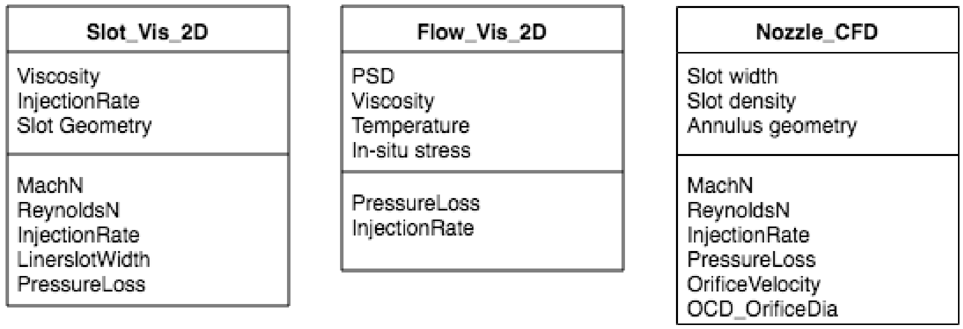


Figure 18: Flow Evaluation Features

including changes in flow, saturation, temperature, or chemical environment (including salinity and pH) (Fermaniuk, 2013; Mahmoudi, Fattahpour, Nouri, & Leitch, 2016).

### 4.4.2 Detailed Flow Expert Feature

The Phenomenon Features defined in chapter 3 called for a number of methods relating to flow:

+getMachN()
+getOrificeVelocity()
+getReynoldsN()
+updateICD_orificeDia()
+updateInjectionRate()
+updateLinerslotLenght()
+updateLinerslotWidth()
+updateOCD_orificeDia()
+updatePressureLoss()

Each of these methods relates to calculating or otherwise determining an important physical flow parameter, such as Mach number, Reyonolds number, or flow velocity; design parameter such as slot length, width, orifice diameter; and functional system parameters such as pressure loss and injection rates.

Simulation is often the most cost-effective way to explore the design space, which is an inherently iterative process. This requires a good computational model of the domain of interest that accurately represent the behavior of the real system. The Nozzle_CFD class can be fulfilled by the Computational Fluid Dynamics model developed by Li et al, which itself uses feature modelling concepts to coordinate and automate the intelligent modelling of complex flow regimes (L. Li, Lange, Xu, Jiang, & Ma, 2018). In the outflow case, the design of the flow control device should be optimized to maximize the evenness of heat being injected into the reservoir. The improper placement or geometry of FCD ports can generate recirculation and low pressure zones inside the wellbore, which will cause inflow through the sand control, potentially pulling erosive sand across the screen. CFD models can be coupled with a design optimization algorithm which has enabled the autonomous refinement of mechanical designs (L. Li et al., 2016). These models can be refined to simulate more complex phenomena, such as wet steam, but many of these phenomena must be validated experimentally.

In some cases, it is more convenient, accurate, and expedient to use experimental models rather than computational simulations for design refinement. The flow near the wellbore and through sand control apertures is typically characterized as Creep Flow, with Reynolds numbers less than 1. Neither flow through porous media nor open channel flow have been studied in great detail at such slow flow rates, especially when the fluids are highly complex, such as with multiphase mixtures or non-Newtonian fluids. Particle tracking velocimetry (PIV) can be used to model the flow through porous media as it approaches the sand control, the open channel flow through the sand control device, and the interaction of the production flow with the annular flow inside the completion liner. Sen et al describe how this technique can be used to observe flow through porous media (Sen, Nobes, & Mitra, 2012), allowing for the examination of pressure drop and fines transport in the near wellbore region.  Several studies have shown similar methods to observe the flow through orifices and slots, allowing for the examination of the velocity fields at extremely low flow rates and how those velocity fields may affect the deposition of foulants within slotted liner slots (Ansari, Rashid, Waghmare, Ma, & Nobes, 2015a; Ansari et al., 2017; Rasimarzabadi, 2016). These two experiments (flow through porous media and flow through slots) are modelled as Slot_Vis_2D and Flow_Vis_2D.

## 4.5 Sand Control Domain

### 4.5.1 Defining the Sand Control Mechanics Phenomenon

Sand control completions are installed to support the wellbore from collapse, and must strike an important balance: They must control the production of sand, while allowing mobilized fine materials to be produced to avoid the buildup of low permeability 'skin' near the wellbore (Fattahpour et al., 2016). The particles which must be produced are any particles which may become mobile in the reservoir, and includes clay, scale, and fine sand. The size of sand particles which are permissible for production is an important consideration: The primary particles of concern are those that are small enough to mobilized in the sand pack and migrate towards the completion. These particles are those that are smaller than the pore throat diameter, which is a function of the particle size distribution and particle shape distribution of the reservoir sand. Such fine sand must be allowed to pass through the sand control device and produced with the production fluid. Larger particles immediately adjacent to the sand control liner may pass through the sand control under some conditions: it is important that these sand grains pass completely through the sand control aperture (rather than being lodged in the slot), they should be small enough that they are carried to surface with the production fluid rather than settling in the horizontal well, and the flow rate of particles must be low enough that they do not damage the production pumps and surface equipment: valves and elbow fittings at the wellhead are especially suscepitble to erosion and corrosion-erosion.

Sand control apertures are more prone to plugging as they get smaller, and more prone to sand production as they get larger. Thus, the objective of sand control design is to specify apertures which are as large as possible, but not too large. Mahmoudi (Mahmoudi, 2016) investigates the acceptable sanding limits, and while he concedes that the acceptable limit is highly dependent on a number of factors, proposes a rule-of-thumb limit of 0.12-0.15 pounds of sand per square foot of completion over the life of the well.

Several mechanisms have been described to account for the exclusion of solid particles in the flowing field. These mechanisms include: Size exclusion, where the particle is physically larger than the aperture; Surface deposition, where attractive forces such as van der Waals electrostatic and hydration forces cause particles to adhere; and Multi-particle bridging, where arches of particles bridge the aperture and are stabilized either hydrodynamically or mechanical forces (Mahmoudi, 2016).

The stability of each of these mechanism varies greatly. The stability of size exclusion is typically very high, unless the particle has a very high aspect ratio and is able to rotate and jam in the slot during transit. The stability of surface deposition is highly dependent on the chemical environment, including the surface energies of the sand control liner and particles, the salinity and pH of connate water, and the forces acting on the deposited particle (Mahmoudi, Fattahpour, Nouri, & Leitch, 2016). The stability of multi-particle bridges is dependent on the number and size of grains incorporated in the bridge, the shape and surface texture of those particles, capilarity of the wetting phase of the resrvoir, and the mechanical and hydrodynamic forces acting on the bridge (Mahmoudi, 2016). The degree to which each of these mechanisms is found in a real reservoir is strongly dependent on the distribution of particle sizes, minerology and chemical environment of the reservoir, and the slot size, surface characteristics of the sand control liner, and the flow through the completion (Mahmoudi et al., 2015).

If we can model the liklihood of each bridging mechanism using the probabilities of each of the factors listed above and model the stability of each mechanism, we can then model the expected rate of solids production for each well (or distinct zone within a well), and design our sand control strategy accordingly. There have been many studies on optimizing the design of slots in slotted liner. Fattahpour et al (Fattahpour et al., 2016) provide a comprehensive history and review of sand control literature in the SAGD domain. They identify several main areas of active research including sand characterization, criteria for sand control design, evaluation of sand control devices, and explore the failure of sand control. They identify Open Flow Area (OFA) as a critical factor in the flow capacity of sand control design, but acknowledge that OFA is a significant driver of completion cost, and that therefore the flow capacity, and thus OFA, must be carefully considered. In particular, they observe that since high-velocity flow in the vicinity of the well completion may cause fines movement which will lead to reduction in near-wellbore permeability, that large flow rates through the sand control completion may not be desired.

The industry standard for verifying slot designs in the heavy oil industry was developed and popularized by Benyon (Bennion et al., 2009b; Bennion, Ma, Thomas, & Romanova, 2007; Crowell et al., 1991). These single-slot tests used sand obtained from core samples packed into a cylinder with a flow-conditioning mesh at one end and a slotted coupon at the other. Oil, water, and gas is pumped at varying rates and compositions, and the pressure drop across the coupon is measured. Fermaniuk developed, based on these works, a semi-empirical design model (Fermaniuk, 2013). The objective of this model is to determine the required slot size, density, and cross-sectional geometry to maximize performance, minimize pressure drop, and minimize plugging. More recent efforts have included the design of experimental apparatus which have multiple slots (Mahmoudi, Fattahpour, Nouri, Rasoul, & Leitch, 2016) and radially converging flow (Anderson, 2017), in order to more accurately represent the flow fields within the porous media approaching the sand control device.

### 4.5.2 Detailed Sand Control Expert Features

The Phenomenon Features defined in chapter 3 called for a number of methods relating to sand control:

```
+getFinesProd()
+updateOpenArea()
+updateRes_permeability
+oprimize_FCD()
+optimize_slot()
+getcSOR()
+getInjectionRate()
+getOpenArea()
+getProductionRate()
```

These required functionalities can be provided by three expert evaluation features: Sand_Retention, Scaled_Completion, and Sand_Characterization.

Sand retention tests have long been used to improve confidence in sand control design. Completions are expensive to install and must perform for the life of the well. Consequences of poor performance are far reaching and severe: Plugging of either the sand control or near-wellbore sands will cause a premature reduction in production rates; Production of excess sand is extremely costly to mitigate and can cause premature failure of downstream equipment. The Sand Retention Test (SRT) uses a multi-slot sand control coupon with a sand pack containing minimal stress. This test is an extension of a slurry test, and is appropriate for assessing sand production and fines migration in the early stages of a well's life. The Scaled Completion Test (SCT) uses a similar configuration of coupon and sand pack, but significant stress can be applied to the sand, simulating the near wellbore condition after several years of production. these tests allow for fines migration and sand production be assessed under a variety of conditions.

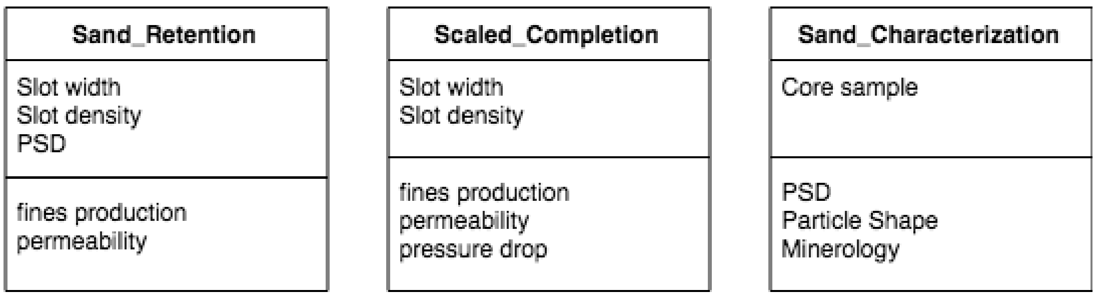


Figure 19: Sand Control Evaluation Features

Underlying both of these experimental tests is the comprehensive characterization of the reservoir sands themselves. This includes the particle size distribution and grain shape, measured by optical analysis (Mahmoudi et al., 2015); and minerology and composition of fine materials, commonly measured by XRD (Mahmoudi, 2016).

### 4.6 Coordinating the Activities of a Unified Design Process

The Expert Features defined in the previous sections, when instantiated as objects, make up the task list in our design process. By following the definitions of those expert features back through their relations to both the Application Feature Module and Unified Feature Module, their dependencies can be clearly mapped. Using a Design Structure Matrix we can represent the dependencies and use the methods described in Chapter 2 to better coordinate those activities.

Figure 20 shows the engineering design tasks specified in the previous section, grouped by expert area: Tasks 1 ansd 2, Corrosion and Fouling, have closely aligned expertise; Tasks 3-5 all relate to fluid dynamics and flow characterization; Tasks 6-8 all specifically deal with sand control testing. It is tempting to co-locate the apparatus and personnel responsible for these tasks in the grouping just described, as they are natural colleagues, and proceed through the task execution in the order shown in Figure 20. Dependencies were mapped according to the specifications in the design feature and phenomenon feature associations presented in Figure 13 and Figure 16 and listed in the order that they were presented in the previous sections of this chapter. It is obvious due to the large number of reverse-dependencies indicated above the diagonal that performing the engineering design tasks in that order would result in a great deal of rework, suggesting that the "natural" groupings by expert area are sub-optimal.

| Name | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| Corrosion | 1 | 1 | | 1 | | 1 | | | 1 |
| Fouling | 2 | 1 | 2 | 1 | 1 | | 1 | 1 | 1 |
| Slot_Vis_2D | 3 | | 1 | 3 | | | 1 | | 1 |
| Flow_Vis | 4 | | | | 4 | | | 1 | 1 |
| Nozzle_CFD | 5 | | | 1 | 1 | 5 | | 1 | |
| Sand_Retention | 6 | | 1 | 1 | | | 6 | | 1 |
| Scaled_Completion | 7 | | | | | | 1 | 7 | 1 |
| Sand_Characterization | 8 | | | | | | | | 8 |

Figure 20: Unpartitioned Design Structure Matrix

| Name | | 8 | 3 | 6 | 4 | 5 | 7 | 1 | 2 |
|---|---|---|---|---|---|---|---|---|---|
| Sand_Characterization | 8 | 8 | | | | | | | |
| Slot_Vis_2D | 3 | 1 | 3 | 1 | | | | | 1 |
| Sand_Retention | 6 | 1 | 1 | 6 | | | | | 1 |
| Flow_Vis | 4 | 1 | | | 4 | | 1 | | |
| Nozzle_CFD | 5 | | 1 | | 1 | 5 | 1 | | |
| Scaled_Completion | 7 | 1 | | 1 | | | 7 | | |
| Corrosion | 1 | 1 | 1 | | | 1 | | 1 | |
| Fouling | 2 | 1 | 1 | 1 | 1 | | 1 | 1 | 2 |

Figure 21: Partitioned Design Structure Matrix

Reordering, or partioning, the DSM can save considerable rework. The partitioned DSM is shown in Figure 21 with the same list of tasks rearranged. Most of the dependencies now lie below the diagonal, which indicates that the tasks proceed largely in order of dependence. Note that the “natural” groupings presented in Figure 20 are not preserved: One major takeaway from this exercise is that it does not make much sense from a design system efficiency point of view to group design tasks by expert area, but rather by information flow. Knowing how these tasks should be ordered also allows for the prioritization of opportunities to couple and automate design tasks.

There are two important groupings that can be deduced from the partitioned DSM, and it is worth discussing each in some detail:

The first design grouping consists of task 3 and task 6. These two tasks are “tightly coupled”, and should therefore be performed in parallel, and the methods designed in such a way to allow for efficient iteration and rework. These two tasks are also dependent on the Fouling model, which is sequenced later in the design activities due to it’s dependence on a great number of downstream factors. Rather than allowing this dependence to force large iterations of the entire design exercise, there are two options available to us. We can design an additional "lightweight fouling test” which is not dependent on tasks 4, 7, and 1, and insert that task in between tasks 6 and 4. This fouling test may therefore be a “conceptual level” test which makes some rough assumptions about the factors which cause the detailed fouling study to have so many dependencies. Our other option is to proceed through to the end of the study, ignoring the dependencies of task 2 on tasks 3 and 6, but perform a “verification check” at the end of the process to quantify the effect of ignoring this dependency on the performance of the system. If the effect is large or if the client’s performance demands are very high then the expense of large-scale iterations may be justifiable.

The second design grouping consists of tasks 4, 5, and 7. These tasks, as in the previous grouping, should be conducted in parallel, or in close proximity, and the design teams conducting each of these tasks should expect to have to iterate on the results of their work in consideration of the other task's results. It is also worthwhile flagging this grouping as a good area to focus on further development of these engineering tasks, integrating them autonomously wherever possible, or perhaps splitting the tasks so that the management of dependencies and task coupling can be managed more easily.

## 4.7 Implementation of the Unified Feature Design Model

There are two practical ways to implement a design model such as the one described in this thesis. The choice of these two methods depends on the goal of the design effort, and the nature of the expert systems which are being coordinated in the effort. The first is as a stand-alone design tool, where the output of the model is an optimized cyber-physical system design. The other is by coupling the model with another design simulation tool in order to improve the underlying physical model of that tool, and thus its accuracy, to be used for verification of designs and optimization of operational parameters.

### 4.7.1 Design Model

As described in Chapter 3, the stand-alone Unified Feature Model as presented here is designed explicity to enable the coordination of both computational and experimental systems (Numerical simulations, experimental systems, and micro-physical simulations, as shown in Figure 9). The SAGD system described is such a system, with experimental models such as the Sand Retention Test interacting with numerical models such as the Nozzle CFD effort. One of the reasons the optimization of the order of operations, described in section 4.6, is so important is because of the vast mismatch in cycle times: iterations that are relatively inexpensive in a simulation are extremely expensive in the experimental realm. Therefore, the use of this model can only be rationalized in use-cases where precise and accurate optimization is critical.

As a stand-alone system, the Unified Feature Design Model is an important tool for research and development or highly customized design, where deep and precise optimization of the system is desired, or where exploratory work is being conducted. For example, if the objective is to develop or validate more accurate simulation models, the exploration of the complex phenomenon in-depth will be desired. Likewise, in the development of a new tool, method, or other highly customized outcome, or if the design objective requires operating a system outside the normal operational envelope, the cost of implementing the Unified Feature Design Model as a stand-alone system can be justified.

As a stand-alone system, the central "hub" of the Unified Feature Model can call the individual expert features in the appropriate order, serving them the required inputs and seeking and output. In the case of a numerical or empirical simulation the feature's functions can be managed automatically. In the case of an experimental or otherwise human-based function, a work order can be automatically generated which will add the appropriate experiment to the lab's queue. The workflow of the Unified Feature Module is shown in Figure 22, along with its interactions with the other layers in the system.

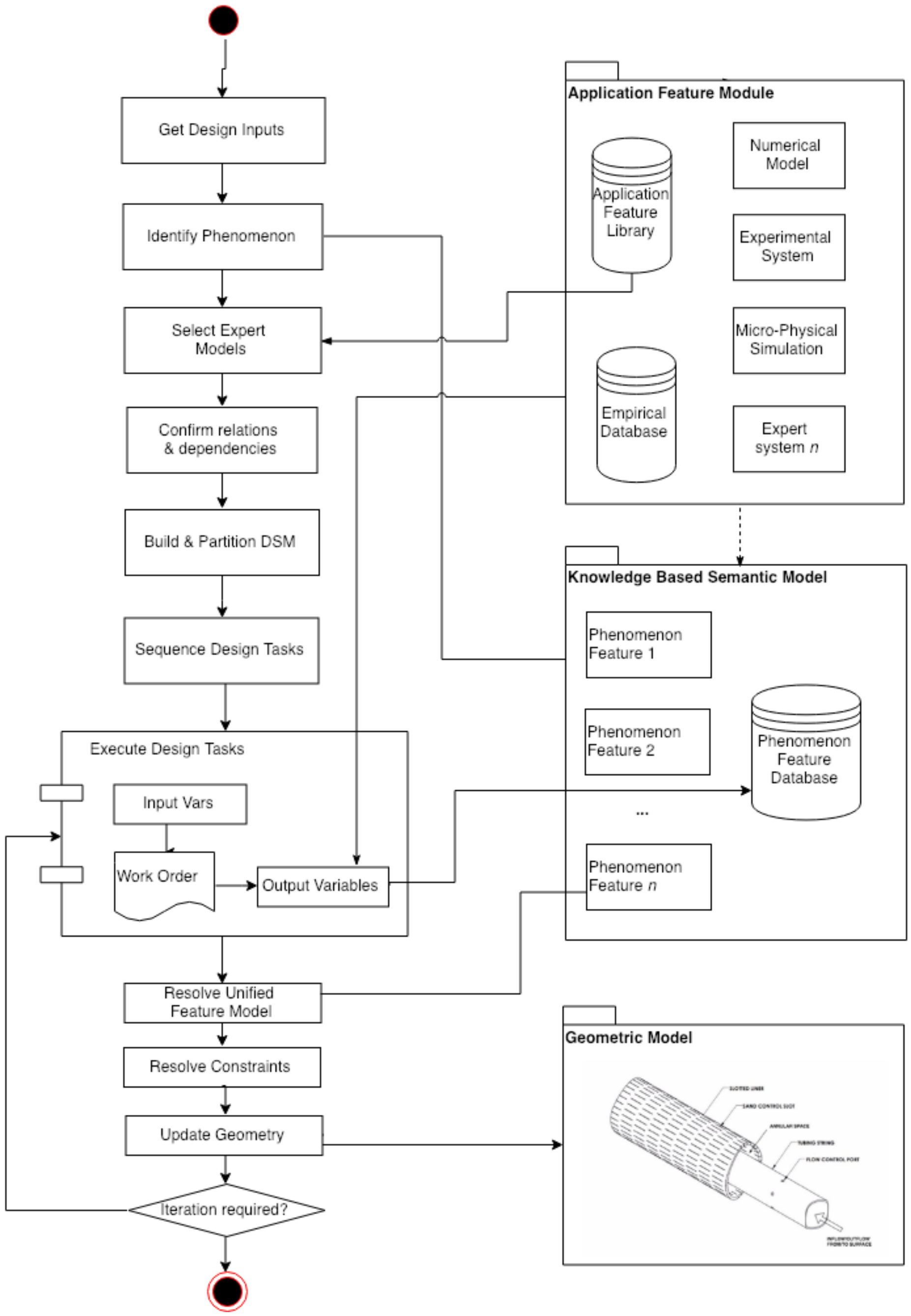


Figure 22: Implementation Activity Diagram for Design Case

### 4.7.2 Verification Model

The second approach to put the Unified Feature Model into practice is to enhance an existing state of the art system-level simulation tool such as STARS (Computer Modelling Group, 2011), effectively inserting the knowledge embodied by the expert systems which make up the Unified Feature Model into the system level model. This approach can be useful:

1) Early in a design phase where different technologies are being evaluated, allowing for a relatively rapid sweep of the design phase;
2) Late in the design phase during system verification, where a design solution must be tested before field implementation;
3) As a way to test and optimize operational parameters, by simulating the performance of the system over the expected service life.

The biggest limitation this approach is where the Unified Feature Design Model depends on physical experimental systems (such is the case in the proposed SAGD model). Experiments are very slow, with cycle times on the order of hours or days, compared to simulation elements which can run at many cycles per second. Therefore the run time of the feature set (times the number of expected iterations) will be the factor which limits the applicability of the model and drives the implementation strategy.

As an example, to implement the proposed SAGD Unified Feature Design Model with STARS, the goal is to improve the performance of the STARS model in the near wellbore region by providing a more accurate model for the skin factor (described in Section 3.5). The workflow for this scenario is shown in Figure 23. There are several important distinctions from the design model workflow shown in the previous section. First, due to the iterative nature of the relationship with the comercial reservoir simulator, it is only practical to include simulation modules in the main workflow. However, the experimental modules can play a role in verification: Where verification is anticipated, a work order can automatically be generated.

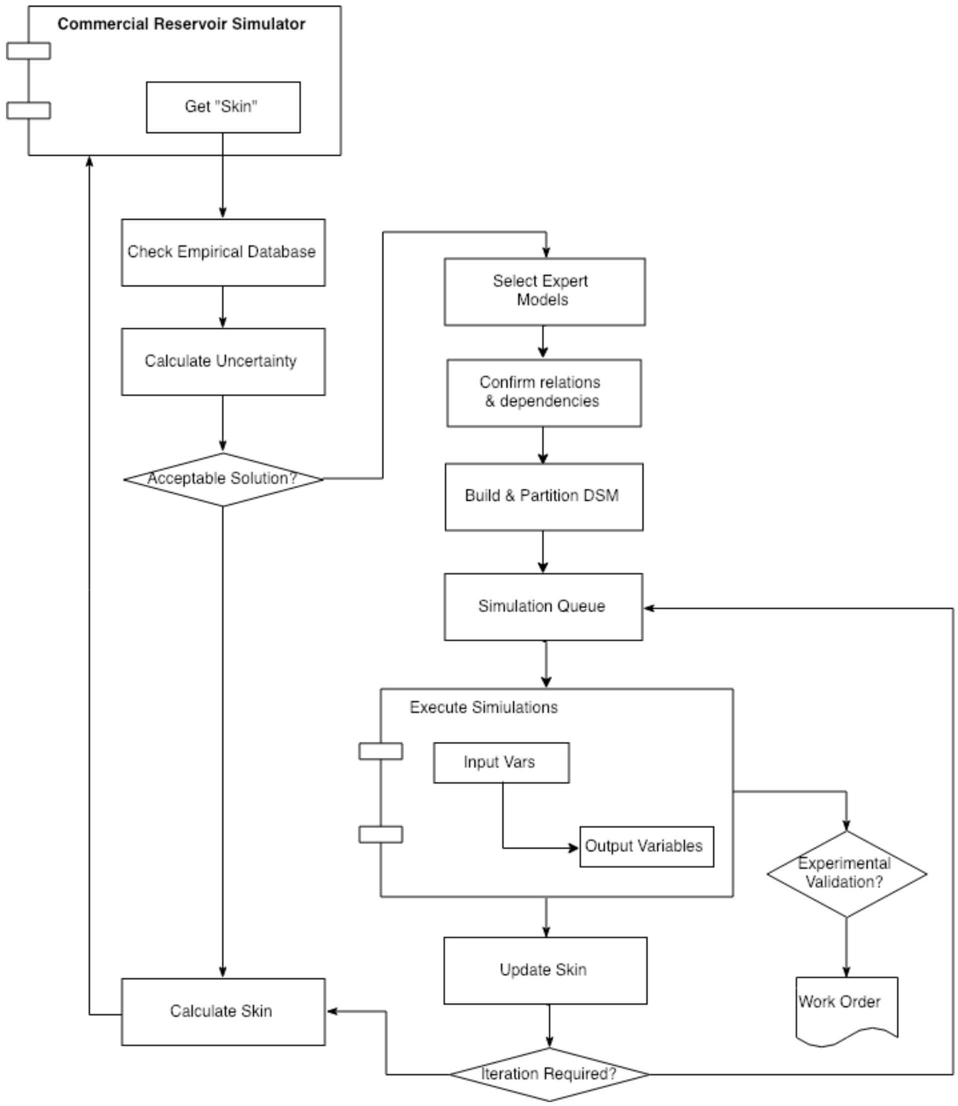


Figure 23: Implementation Activity Diagram for Verification Case

### 4.7.3 Further development of Expert Feature Domains

The most important aspect of the implementation strategy is continual improvement: The goal with any such design system is ultimately to be able to more quickly, inexpensively, and accurately improve system performance. Expert systems which are experimentally based must guide the development of empirical and numerical simulation tools, and expert systems which already have digital toolsets in place must be refined to improve their accuracy and/or runtime.

New tools targeting existing gaps in understanding or new phenomenon must be developed and integrated using the feature based approaches presented here. In the meantime, using the toolsets currently at our disposal, careful records must be kept in order to build out an empirical database of the system's parameters and performance.

# 5 Conclusion

This thesis explored a number of very high level themes, in an attempt to formally relate very different expert systems to each other in the service of a complex design problem. The first chapter described the context for this work and specified the research hypothesis. The hypothesis, in short, is that in order to solve a complex engineering design challenge, that knowledge management methods can be used to scope, coordinate, and consolodate a dispersed group of experts to ultimately solve the problem.

Chapter 2 provided a literature review to outline and support the theory. The organization of engineering design groups and the design of engineering design processes was explored to provide context for the challenges and opportunities of using disbursed experts to solve complex problems. Information technologies used to support knowledge management and design optimization were reviewed, and specifically the concept of unified feature models.

Chapter 3 describes the technical challenge in detail, the Steam-Assisted Gravity Drainage oil etraction method, and the development of tools which optimize the performance of the system. Commercial tools used in industry are described, limitations and opportunities for ongoing development are identified. This chapter explains the various fundamental phenomenon which contribute to the performance of the system, and a mathematical description of the system performance was used to facilitate a functional decomposition of the domain. This was used to identify the key phenomena which map on to the expert domains which will be required to generate a solution. Knowledge models designed to support the flow of knowledge between both experimental and computational expert systems was introduced.

Chapter 4 defines two other semantic knowledge schemas necessary to generate a solution: While the phenomenon features defined in Chapter 3 describe the relationship between the environment and the system, those relationships must be used directly in the design of the mechanical components of the system, and those two layers must be coordinated explicitly. The system was defined using a semantic model. The relationship between the phenomenon features and the design features were made using evaluation features, which are classes that can be instantiated as experimental or computational systems which constitute tasks in the design process. Examples of each of these systems are described. These tasks were related to each other using the dependencies identified in the semantic knowledge models, and coordinated using a Design Structure Matrix in order to determine the optimal task sequencing. Manipulations of the matrix help identify the ideal order of operations, identify key knowledge interfaces, and allow for the anticipation and management of costly iterations.

Finally, the implementation strategy for the Unified Feature Model is explored, both as a stand-alone design model and as a high-performance physics engine to supplement existing system models. This thesis demonstrates how Feature Models can be combined with a conceptual-level design management methodology to optimize design solutions in complex environments. These concepts and methods are lightweight, extensible, scalable, modular, which allows design managers to add additional semantic blocks where needed to describe new phenomenon, design elements, or evaluation systems. The methodologies outlined in this work provide a methodological workflow to aid in the development of Cyber-Phsyicsal Systems to model any phenomenon which has a great deail of multidisciplinary complexity.

## Works Cited


Adams, R. S., Forin, T., Chua, M., & Radcliffe, D. (2016). Characterizing the work of coaching during design reviews, *45*, 30–67. https://doi.org/10.1016/j.destud.2015.12.007

Al-Bahlani, A.-M., & Babadagli, T. (2009). {SAGD} laboratory experimental and numerical simulation studies: A review of current status and future issues. *Journal of Petroleum Science and Engineering*, *68*(3–4), 135–150. https://doi.org/10.1016/j.petrol.2009.06.011

Alberta Energy. (2014). About Oil Sands: Facts and Statistics. Retrieved from http://www.energy.alberta.ca/oilsands/791.asp

Allen, T. J. (1984). *Managing the flow of technology*. MIT University Press Group Ltd.

Anderson, M. (2017). SAGD Sand Control: Large Scale Testing Results. In *SPE Canada Heavy Oil Technical Conference*. Society of Petroleum Engineers. https://doi.org/10.2118/185967-MS

Ansari, S. (2016). Newtonian and Non-Newtonian Flow through mini-channels and micro-scale orifices for SAGD Applications. In *2016 RGL Symposium on SAGD Near Wellbore Physics and Design*.

Ansari, S., Rashid, M. A. I., Waghmare, P. R., Ma, Y., & Nobes, D. (2015a). Newtonian and non-Newtonian flows through micro scale orifices. In *10\textsuperscript{th} Pacific Symposium on Flow Visualization and Image Processing*.

Ansari, S., Rashid, M. A. I., Waghmare, P. R., Ma, Y., & Nobes, D. (2015b). Newtonian and Non-Newtonian flows through micro scale orifices. In *10\textsuperscript{th} Pacific Sympiosium on Flow Visualization and Image Processing*.

Ansari, S., Sabbagh, R., Rasimarzabadi, F., Leitch, M., Waghmare, P. R., & Nobes, D. S. (2017). VISUALIZATION OF AN ELECTRO ELECTROKINETIC DRIVEN FLOW THROUGH MINI-CHANNELS IN SAGD WELLS. In *ASTFE Second Thermal and Fluids Engineering Conference* (p. `). Las Vegas, NV.

Azad, A. (2012). *Rapid SAGD Simulation Considering Geomechanics for Closed Loop Reservoir Optimization*. University of Alberta.

Azad, A., & Chalaturnyk, R. J. (2009). Geomechanical coupling simulation in SAGD process; a linear geometry model. In M. Diederichs & G. Grasselli (Eds.), *ROCKENG09: Proceedings of the 3\textsuperscript{rd} CANUS Rock Mechanics Symposium*.

Azom, P. (2013). *Improved Modelling of the Steam-Assisted Gravity Drainage (SAGD) Process*. University of Texas in Austin.

Bao, X. (2012). *Thermal Simulation and Optimization of SAGD Process: Case Study on Surmount Pilot Project*. University of Calgary.

Belhajjame, K., Jun, Daniel, Z., Kristina, G., Raul, H., Palma, … Goble. (2014). The Research Object Suite of Ontologies: Sharing and Exchanging Research Data andMethods on the Open Web. Retrieved from https://arxiv.org/abs/1401.4307

Belhajjame, K., Zhao, J., Garijo, D., Gamble, M., Hettne, K., Palma, R., … Goble, C. (2015). Using a suite of ontologies for preserving workflow-centric research objects. *Web Semantics: Science, Services and Agents on the World Wide Web*, *32*, 16–42. https://doi.org/10.1016/j.websem.2015.01.003

Bennion, D. B., Gupta, S., Gittins, S., & Hollies, D. (2009a). Protocols for Slotted Liner Design for Optimium SAGD Operation. *Journal of Canadian Petroleum Technology*.

Bennion, D. B., Gupta, S., Gittins, S., & Hollies, D. (2009b). Protocols for slotted liner design for optimum SAGD operation. *Journal of Canadian Petroleum Technology*, *48*(11), 21–26. https://doi.org/10.2118/130441-PA

Bennion, D. B., Ma, T., Thomas, F. B., & Romanova, U. G. (2007). Laboratory Procedures for Optimizing the Recovery from High Temperature Thermal Heavy Oil and Bitumen Recovery Operations. *Proceedings of Canadian International Petroleum Conference*, 14. https://doi.org/10.2118/2007-206

Bernal, M., Haymaker, J. R., & Eastman, C. (2015). On the role of computational support for designers in action, *41*, 163–182. https://doi.org/10.1016/j.destud.2015.08.001

Bhrugubanda, M. (2015). A Review on Applications of Cyber Physical Systems, *2*(6), 728–730.

Bowen, S., Durrant, A., Nissen, B., Bowers, J., & Wright, P. (2016). The value of designers{\textquotesingle} creative practice within complex collaborations, *46*, 174–198. https://doi.org/10.1016/j.destud.2016.06.001

Bradner, E., Iorio, F., & Davis, M. (2014). Parameters tell the Design Story: Ideation and Abstraction in Design Optimization. In *Symposium on Simulation for Architecture and Urban Design*.

Braha, D. (2002). Partitioning Tasks to Product Development Teams. In *Volume 4: 14\textsuperscript{th} International Conference on Design Theory and Methodology, Integrated Systems Design, and Engineering Design and Culture*. {ASME} International. https://doi.org/10.1115/detc2002/dtm-34031

Browning, T. R. (2001). Applying the design structure matrix to system decomposition and integration problems: a review and new directions. *{IEEE} Transactions on Engineering*

*Management*, *48*(3), 292–306. https://doi.org/10.1109/17.946528

Browning, T. R., & Eppinger, S. D. (2002). Modeling impacts of process architecture on cost and schedule risk in product development, *49*(4), 428–442. https://doi.org/10.1109/tem.2002.806709

Butler, R. M. (1994). Steam-Assisted Gravity Drainage: Concept, Development, Performance And Future. *Journal of Canadian Petroleum Technology*, *33*(02), 44–50. https://doi.org/10.2118/94-02-05

Canadian Association of Petroleum Producers. (2016). Oil Sands. Retrieved from http://www.capp.ca/canadian-oil-and-natural-gas/oil-sands

Canadian Energy Research Institute. (2017). *Canadian Oil Sands Supply Costs and Development Projects (2016-2036)*.

Carlson, M. (2006). *Practical Reservoir Simulation: Using, assessing, and developing results.*

Cenovus. (2016). Cenovus Foster Creek update for 2015, (8623).

Chen, G., Ma, Y.-S., Thimm, G., & Tang, S.-H. (2004). Unified Feature Modeling Scheme for the Integration of {CAD} and {CAx}, *1*(1–4), 595–601. https://doi.org/10.1080/16864360.2004.10738303

Chen, H. (2017). Theoretical Foundations for Cyber-Physical Systems: A Literature Review. *Journal of Industrial Integration and Management*, *02*(03), 1750013. https://doi.org/10.1142/S2424862217500130

Chen, X. (2016). *The Study of the Corrosion Behavior of Gas Nitriding Treated L80 Steel in Simulated Environment for the Slotted Liners of SAGD*. University of Alberta. https://doi.org/10.7939/R3DN40648

Computer Modelling Group. (2011). STARS - Thermal & Advanced Process Reservoir Simulator.

Crowell, E. C., Bennion, D. B., Energy, H., Thomas, F. B., & Bennion, D. W. (1991). the Design & Use of Laboratory Tests To Reduce Formation Damage in Oil & Gas Reservoirs.

Dantan, J. Y., Qureshi, A. J., Antoine, J. F., Eisenbart, B., & Blessing, L. (2013). Management of product characteristics uncertainty based on formal logic and characteristics properties model. *{CIRP} Annals - Manufacturing Technology*, *62*(1), 147–150. https://doi.org/10.1016/j.cirp.2013.03.077

Datta, P., & Bhuyan, D. (1980). Practical Analysis and use of Skin Effect. *Society of Petroleum Engineers*, (SPE-9014-MS).

Davis, S. M., & Lawrence, P. R. (1978). Problems of Matrix Organizations, (78303).

de Mast, J. (2007). Integrating the Many Facets of Six Sigma. *Quality Engineering*, *19*(4), 353–361. https://doi.org/10.1080/08982110701458145

deKraker, J. K. (1997). Feature Conversion for Concurrent Engineering.

Eastman, C., & Fereshetian, N. (1994). Information models for use in product design: a comparison. *Computer-Aided Design*. https://doi.org/0010-4485/94/07/0551-22

Edmunds, N., & Peterson, J. (2007). A Unified Model for Prediction of SCSOR in Steam-Based Bitumen Recovery. In *Petroleum Society's 8\textsuperscript{th} Canadian International Petroleum Conference*. Calgary.

Eppinger, S. D. (1991). Model-based Approaches to Managing Concurrent Engineering. *Journal of Engineering Design*, *2*(4), 283–290. https://doi.org/10.1080/09544829108901686

Eppinger, S. D. (2016). *Design Structure Matrix Methods and Applications*. MIT University Press

Group Ltd. Retrieved from http://www.ebook.de/de/product/25236996/steven_d_eppinger_design_structure_matrix_methods_and_applications.html

Fattahpour, V., Mahmoudi, M., Nouri, A., Azadbakht, S., Leitch, M., Fermaniuk, B., & Sutton, C. (2016). A Critical Review of Sand Control Design for SAGD Wells. In *World Heavy Oil Congress 2016*.

Fermaniuk, B. (2013). *Sand Control in Steam Assisted Gravity Drainage (SAGD) Wellbores and Process of Slotted Liner Design and Manufacture*. University of Calgary.

Frenier, W. W., & Ziauddin, M. (2010). A Multifaceted Approach for Controlling Complex Deposits in Oil and Gas Production. *SPE Annual Technical Conference and Exhibition*, (SPE 132707), 1–24. Retrieved from http://www.onepetro.org/mslib/servlet/onepetropreview?id=SPE-132707-MS

Gates, I. D., & Larter, S. R. (2014). Energy efficiency and emissions intensity of {SAGD}. *Fuel*, *115*, 706–713. https://doi.org/10.1016/j.fuel.2013.07.073

Gerhardus H. Koch, M. P. H., & Brongers, and N. G. T. Y. P. V. J. H. P. (2002). Corrosion costs and preventive strategies in the United States. *Summary*, 1–12. https://doi.org/FHWA-RD-01-156

Government of Canada, N. S. and E. R. C. of C. C. D. (n.d.). NSERC – Collaborative Research and Development Grants. Retrieved from http://www.nserc-crsng.gc.ca/Professors-Professeurs/RPP-PP/CRD-RDC_eng.asp

Grogan, P. T., & de Weck, O. L. (2016). Collaboration and complexity: an experiment on the effect of multi-actor coupled design, *27*(3), 221–235. https://doi.org/10.1007/s00163-016-0214-7

Groysberg, B., & Slind, M. (2012). Leadership is a Conversation. *Harvard Business Review*, *3*(4), 413–424.

Guariniello, C., & DeLaurentis, D. (2016). Supporting design via the System Operational Dependency Analysis methodology. https://doi.org/10.1007/s00163-016-0229-0

Holly, C., Mader, M., Soni, S., & Toor, J. (2014). *Alberta Energy, Oil Sands Production Profile: 2004-2014*.

Horváth, I., & Pourtalebi, S. (2015). Fundamentals of a Mereo-Operandi Theory to Support Transdisciplinary Modeling and Co-Design of Cyber-Physical Systems. In *Volume 1A: 35\textsuperscript{th} Computers and Information in Engineering Conference*. {ASME} International. https://doi.org/10.1115/detc2015-46702

International Standards Organization. (2015). *ISO 9001:2015(en) Quality Management Systems - Requirements*. Retrieved from https://www.iso.org/iso-9001-quality-management.html

Ji, Y. (2013). *Fundamental Understanding of the Flocculation of Mineral Tailings in High Salinity Water*. University of Alberta.

Kaiser, T. M. V, Wilson, S., & Venning, L. A. (2002). Inflow Analysis and Optimization of Slotted Liners. *{SPE} Drilling {&} Completion*, *17*(04), 200–209. https://doi.org/10.2118/80145-pa

Krishnan, V., Eppinger, S. D., & Whitney, D. E. (1997). Simplifying Iterations in Cross-Functional Design Decision Making. *Journal of Mechanical Design*, (4), 485–493. https://doi.org/10.1115/1.2826394

Kumar, A., Oballa, V., & Card, C. (2010). Fully-Coupled Wellbore Design and Optimization for Thermal Operations. In *Canadian Unconventional Resources and International Petroleum Conference*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/137427-ms

Le H.N.; Wynn, D. C.; Clarkson, P. J. (2010). Modelling the Influence of Uncertainty -- Process Architecture and Feedback Dynamics on PD Projects. In *DSM 2010: Proceedings of the 12\textsuperscript{th} International DSM Conference, Cambridge, UK* (pp. 113–124).

Li, L., Lange, C. F., & Ma, Y. (2015). Modelling of Outflow Control Device Applied in Steam Assisted Gravity Drainage. In *23\textsuperscript{rd} Annual Conference of Computational Fluid Dynamics*. Waterloo.

Li, L., Lange, C. F., & Ma, Y. (2016). Modelling of Outflow Control in Steam Assisted Gravity Drainage Process. In *2016 RGL Symposium on SAGD Near Wellbore Physics and Design*.

Li, L., Lange, C. F., Xu, Z., Jiang, P., & Ma, Y. (2018). Feature-based intelligent system for steam simulation using computational fluid dynamics. *Advanced Engineering Informatics*, *38*(March), 357–369. https://doi.org/10.1016/j.aei.2018.08.011

Li, L., Lange, C., & Ma, Y. (2018). Artificial Intelligence Aided CFD Analysis Regime Validation and Selection in Feature-baswed Cyclic CAD/CFD Interaction Process. *Computer-Aided Design and Applications*, (15).

Li, M., & Li, D. (2012). Modular Decomposition Method Based on Design Structure Matrix and Application. *Telkomnika*, *10*(8), 2169–2175.

Li, Z., Fortenberry, R., Luo, H., & Delshad, M. (2017). An examination of the concept of apparent skin factor in modeling injectivity of non-Newtonian polymer solutions. *Journal of Petroleum Science and Engineering*, *158*(July), 160–174. https://doi.org/10.1016/j.petrol.2017.08.044

Liu, Y., Peng, Y., Wang, B., Yao, S., & Liu, Z. (2017). Review on cyber-physical systems. *IEEE/CAA Journal of Automatica Sinica*, *4*(1), 27–40. https://doi.org/10.1109/JAS.2017.7510349

Lu, Q., Huang, J., Maan, O., Liu, Y., & Zeng, H. (2018). Probing molecular interaction mechanisms of organic fouling on polyamide membrane using a surface forces apparatus: Implication for wastewater treatment. *Science of the Total Environment*, *622–623*, 644–654. https://doi.org/10.1016/j.scitotenv.2017.12.022

Luo, H., Leitch, M., Behnamian, Y., Ma, Y., Zeng, H., & Luo, J.-L. (2015). Development of electroless Ni{\textendash}P/nano-{WC} composite coatings and investigation on its properties. *Surface and Coatings Technology*, *277*, 99–106. https://doi.org/10.1016/j.surfcoat.2015.07.011

Luo, H., Leitch, M., Zeng, H., & Luo, J.-L. (2018). Characterization of microstructure and properties of electroless duplex Ni-W-P/Ni-P nano-ZrO 2 composite coating. *Materials Today Physics*, *4*, 36–42. https://doi.org/10.1016/j.mtphys.2018.03.001

Luo, J., & Zeng, H. (2015). *Award Details: Corrosion mechanism and corrosion control of slotted liners*. *NSERC*.

Ma, Y.-S., Britton, G. A., Tor, S. B., & Jin, L. Y. (2006). Associative assembly design features: concept, implementation and application, *32*(5–6), 434–444. https://doi.org/10.1007/s00170-005-0371-8

Ma, Y.-S., & Tong, T. (2003). Associative feature modeling for concurrent engineering integration. *Computers in Industry*, *51*(1), 51–71. https://doi.org/10.1016/s0166-3615(03)00025-3

Ma, Y. (Ed.). (2013). *Semantic Modeling and Interoperability in Product and Process Engineering*. Springer London. https://doi.org/10.1007/978-1-4471-5073-2

Ma, Y., Chen, G., & Thimm, G. (2008). Change propagation algorithm in a unified feature modeling scheme. *Computers in Industry*, *59*(2–3), 110–118. https://doi.org/10.1016/j.compind.2007.06.006

Ma, Y. S., Tang, S. H., & Chen, G. (2007). A Fine-grain and Feature-oriented Product Database for Collaborative Engineering. *Collaborative Product Design and Manufacturing Methodologies and Applications*, 109–136. https://doi.org/10.1007/978-1-84628-802-9_6

Mahmoudi, M. (2016). New Sand Control Design Criteria and Evaluation Testing for Steam Assisted Gravity Drainage (SAGD) Wellbores.

Mahmoudi, M., Fattahpour, V., Nouri, A., & Leitch, M. (2016). An Experimental Investigation of the Effect of {pH} and Salinity on Sand Control Performance for Heavy Oil Thermal Production. In *{SPE} Canada Heavy Oil Technical Conference*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/180756-ms

Mahmoudi, M., Fattahpour, V., Nouri, A., & Leitch, M. (2017). An Experimental Evaluation of Pore Plugging and Permeability Reduction Near {SAGD} Sand Control Liners. In *{SPE} Canada Heavy Oil Technical Conference*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/184999-ms

Mahmoudi, M., Fattahpour, V., Nouri, A., Rasoul, S., & Leitch, M. (2016). The Effect of Slot Width and Density on Fines Migration and Production in SAGD Operations. In *World Heavy Oil Congress 2016*.

Mahmoudi, M., Fattahpour, V., Nouri, A., Yao, T., Baudet, B. A., & Leitch, M. (2015). Oil Sand Characterization for Standalone Screen Design and Large-Scale Laboratory Testing for Thermal Operations. In *{SPE} Thermal Well Integrity and Design Symposium*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/178470-ms

Mann, D., & Domb, E. (n.d.). TRIZ -BASED SYSTEMATIC INNOVATION : The Space Between Inventive Principle and Design Solution.

Matanovic, D., Cikes, M., & Moslavac, B. (2012). *Sand Control in Well Construction and Operation*. Springer Berlin Heidelberg. Retrieved from http://www.ebook.de/de/product/19292877/davorin_matanovic_marin_cikes_bojan_moslavac_sand_control_in_well_construction_and_operation.html

McCord, K. R. (1993). Managing the Integration Problem in Concurrent Engineering. *Department of Mechanical Engineering*. https://doi.org/10.1111/1467-8276.00319

Medina, M. (2013). Design and Field Evaluation of Tubing Deployed Passive Outflow Control Devices in {SAGD} Injection Wells. In *{SPE} Heavy Oil Conference-Canada*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/165563-ms

Mohammadi, F., & Luo, J. (2011). Effect of cold work on erosion-corrosion of 304 stainless steel. *Corrosion Science*, *53*(2), 549–556. https://doi.org/10.1016/j.corsci.2010.09.059

Mojarab, M., Harding, T. G., & Maini, B. B. (2011). Improving the {SAGD} Performance by Introducing a New Well Configuration. *Journal of Canadian Petroleum Technology*, *50*(SPE-146626-PA), 9–18. https://doi.org/10.2118/146626-pa

Muccino, J. C., Gray, W. G., & Ferrand, L. A. (1998). Toward an improved understanding of multiphase flow in porous media. *Reviews of Geophysics*, *36*(3), 401–422. https://doi.org/10.1029/98RG00878

National Resources Canada. (2017). Energy Fact Book 2016-2017.

Nguyen, H. X., Bae, W., Tran, X. V, & Chung, T. (2011). Experimental Design to Optimize Operating Conditions for SAGD Process, Peace River Oilsands, Alberta. In *Society of*

*Petroleum Engineers*.

Nobes, D., & Lange, C. (2015). *Award Details: The near field fluid mechanics of SAGD wells*.

Nouri, A., & Chan, D. (2015). *Award Details: Comprehensive laboratory and numerical investigation of SAGD completions*.

NOV. (2014). *Holing and Slotting of Casing*. Retrieved from http://www.nov.com/uploadedFiles/Content/Segments/Completion_and_Production_Solutions/Intervention_and_Stimulation_Equipment/Elmar/TUBULAR_Completion_Equipment/TUBULAR.pdf

NSERC. (2018). Award Details: Interoperability in knowledge driven collaborative engineering, 2018.

Oballa, V., Coombe, D. A., & Buchanan, L. (1997). Aspects of Discretized Wellbore Modelling Coupled to Compositional/Thermal Simulation. *Journal of Canadian Petroleum Technology*, *36*(04). https://doi.org/10.2118/97-04-04

Ohen, H. A., & Civan, F. (1991). Predicting Skin Effects Due to Formation Damage by Fines Migration. In *{SPE} Production Operations Symposium*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/21675-ms

Oil Sands Discovery Center. (2014). *Facts about Alberta' s oil sands and its industry*. Retrieved from http://history.alberta.ca/oilsands/resources/resources.aspx

Patel, K., Aske, E. M., & Fredriksen, M. (2013). Integrating Reservoir Simulator and Model Predictive Control Software for Automating SAGD Well Pair Operations. In *SPE Heavy Oil Conference*.

Pourtalebi, S., & Horváth, I. (2016). Towards a methodology of system manifestation features-based pre-embodiment design. *Journal of Engineering Design*, *27*(4–6), 232–268. https://doi.org/10.1080/09544828.2016.1141183

Rahman, R. S. M., & Ma, Y.-S. (2013). An Example of Feature Modeling Application: Smart Design for Well-Drilling Systems (pp. 53–87). https://doi.org/10.1007/978-1-4471-5073-2_3

Rahmati, E. (2016). *Numerical Assessment of Caprock Integrity in SAGD Operations Considering Mechanical Anisotropic Behavior of Shale Layers*. Univeristy of Alberta. https://doi.org/10.7939/R3804XQ7T

Rahmati, E., Nouri, A., Fattahpour, V., & Trivedi, J. (2017). Numerical assessment of the maximum operating pressure for SAGD projects considering the effects of anisotropy and natural fractures. *Journal of Petroleum Science and Engineering*, *157*(July), 196–206. https://doi.org/10.1016/j.petrol.2017.07.005

Rasimarzabadi, F. (2016). Measurement of the Flow Field out of High Aspect Ratio Slots. In *2016 RGL Symposium on SAGD Near Wellbore Physics and Design*.

Rasimarzabadi, F., Leitch, M., Ansari, S., & Nobes, D. S. (2016). Flow Visualization and for Performance and Measurement across Sand and Control and Orifices. In *SPE Latin America and Caribbean Heavy and Extra Heavy Oil Conference*. Society of Petroleum Engineering.

Rasoulifar, G., Eckert, C., & Prudhomme, G. (2014). Supporting communication between product designers and engineering designers in the design process of branded products: a comparison of three approaches. *CoDesign*, *10*(2), 135–152. https://doi.org/10.1080/15710882.2014.923912

Renpu, W. (2011). *Advanced Well Completion Engineering* (3\textsupe). Elsevier. Retrieved from https://library.ualberta.ca/catalog/5356138

Rolstadås, A., Hetland, P. W., Jergeas, G. F., & Westney, R. E. (2011). *Risk Navigation Strategies for Major Capital Projects*. Springer London. https://doi.org/10.1007/978-0-85729-594-1

Romanova, U. G., & Ma, T. (2013). An Investigation of the Plugging Mechanisms in a Slotted Liner from the Steam Assisted Gravity Operations. In *SPE European Formation Damage Conference and Exhibition, Noordwijk, The Netherlands*.

Ryen, E. (2008). Overview of the Systems Engineering Process.

Sajadfar, N., Xie, Y., Liu, H., & Ma, Y.-S. (2013). A Review of Data Representation of Product and Process Models. In *Springer Series in Advanced Manufacturing* (pp. 31–51). Springer Nature. https://doi.org/10.1007/978-1-4471-5073-2_2

Samuel, P., & Ohler, M. (2015). Classification of {TRIZ} Techniques Using a Cognition-Based Design Framework, *131*, 984–992. https://doi.org/10.1016/j.proeng.2015.12.410

Sen, D., Nobes, D. S., & Mitra, S. K. (2012). Optical measurement of pore scale velocity field inside microporous media. *Microfluidics and Nanofluidics*, *12*(1–4), 189–200. https://doi.org/10.1007/s10404-011-0862-x

Shahamiri, A., Heidari, M., Buchanan, W. L., & Nghiem, L. X. (2015). A {CFD} Compositional Wellbore Model for Thermal Reservoir Simulators. In *{SPE} Annual Technical Conference and Exhibition*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/175056-ms

Sobek, D. K., & Jain, V. K. (2007). Relating Design Process to Quality: A Virtual Design of Experiments Approach. *Journal of Mechanical Design*, *129*(5), 483. https://doi.org/10.1115/1.2712215

Sosa, M. E., Eppinger, S. D., Pich, M., McKendrick, D. G., & Stout, S. K. (2002). Factors that influence technical communication in distributed product development: an empirical study in the telecommunications industry, *49*(1), 45–58. https://doi.org/10.1109/17.985747

Spear, S., & Bowen, H. K. (1999). Decoding the DNA of the Toyota Production System. *Harvard Business Review*, *77*(5), 96–106. https://doi.org/http://search.ebscohost.com/login.aspx?direct=true&db=buh&AN=2216294&site=ehost-live

*Suncor MacKay River Project 2016 AER Performance Presentation*. (2016).

Surowiecki, J. (2008, May 12). The Open Secret of Success. *The New Yorker*. Retrieved from https://www.newyorker.com/magazine/2008/05/12/the-open-secret-of-success

Swarbrick, T., & Muller, M. (2016). Innovative Experimental Design Workflows for Coupled Models. In *{SPE} Asia Pacific Oil {&} Gas Conference and Exhibition*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/182340-ms

Tahera, K., Wynn, D. C., Earl, C., & Eckert, C. M. (2018). Testing in the incremental design and development of complex products. *Research in Engineering Design*, *0*(0), 0. https://doi.org/10.1007/s00163-018-0295-6

Tan, T. B., Butterworth, E., & Yang, P. (2002). Application of a Thermal Simulator with Fully Coupled Discretized Wellbore Simulation to {SAGD}. *Journal of Canadian Petroleum Technology*, *41*(PETSOC-02-01-01), 25–30. https://doi.org/10.2118/02-01-01

Tang, S.-H., Chen, G., & Ma, Y.-S. (2013). Fundamental Concepts of Generic Features (pp. 89–115). https://doi.org/10.1007/978-1-4471-5073-2_4

Taubner, S. P., Subramanian, V., & Kaiser, T. M. V. (2015). Assessing Subcool Control Issues in {SAGD} Producers and Methods for Mitigation. In *{SPE} Thermal Well Integrity and Design Symposium*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/178453-ms

Thebeau, R. (2001). Knowledge Management of System Interfaces and Interactions for Product Development Processes.

Toyota (GB) PLC. (n.d.). 13 Pillars of the Toyota Production System.

Trappey, A. J. C., Trappey, C. V., Govindarajan, U. H., Sun, J. J., & Chuang, A. C. (2016). A Review of Technology Standards and Patent Portfolios for Enabling Cyber-Physical Systems in Advanced Manufacturing. *IEEE Access*, *4*, 7356–7382. https://doi.org/10.1109/ACCESS.2016.2619360

Ulrich, K., & Eppinger, S. (2003). *Product Design and Development*. McGraw-Hill/Irwin.

Unger, D. W., & Eppinger, S. D. (2009). Comparing product development processes and managing risk. *International Journal of Product Development*, *8*(4), 382. https://doi.org/10.1504/ijpd.2009.025253

van Essen, G., den Hof, P. Van, & Jansen, J.-D. (2013). A Two-Level Strategy to Realize Life-Cycle Production Optimization in an Operational Setting. *{SPE} Journal*, *18*(06), 1057–1066. https://doi.org/10.2118/149736-pa

van Everdingen, A. F. (1953). The Skin Effect and Its Influence on the Productive Capacity of a Well. *Journal of Petroleum Technology*, *5*(06), 171–176. https://doi.org/10.2118/203-g

VanderValk, P. A., & Yang, P. (2007). Investigation of Key Parameters in {SAGD} Wellbore Design and Operation. *Journal of Canadian Petroleum Technology*, *46*(PETSOC-07-06-02), 49–56. https://doi.org/10.2118/07-06-02

Vicente, R., Sarica, C., & Ertekin, T. (2001). A Two-Phase Model Coupling Reservoir and Horizontal Well Flow Dynamics. In *{SPE} Latin American and Caribbean Petroleum Engineering Conference*. Society of Petroleum Engineers ({SPE}).

https://doi.org/10.2118/69570-ms

Wang, J., Xie, L., Zhang, H., Liu, Q., Liu, Q., & Zeng, H. (2017). Probing interactions between sphalerite and hydrophobic/hydrophilic surfaces: Effect of water chemistry. *Powder Technology*, *320*, 511–518. https://doi.org/10.1016/j.powtec.2017.07.084

Wang, Q. Y., Behnamian, Y., Luo, H., Wang, X. Z., Leitch, M., Zeng, H., & Luo, J. L. (2017). Anticorrosion performance of chromized coating prepared by pack cementation in simulated solution with H2S and CO2. *Applied Surface Science*, *419*, 197–205. https://doi.org/10.1016/j.apsusc.2017.05.001

West, M. (1996). *Developing High Quality Data Models*.

Wubneh, A. T. (2011). FEATURE BASED CONCEPTUAL DESIGN MODELING AND OPTIMIZATION OF VARIATIONAL MECHANISMS.

Wynn, D. C., & Clarkson, P. J. (2018). Process models in design and development. *Research in Engineering Design*, *29*(2), 161–202. https://doi.org/10.1007/s00163-017-0262-7

Wynn, D. C., & Eckert, C. M. (2016). Perspectives on iteration in design and development. https://doi.org/10.1007/s00163-016-0226-3

Xie, J., Jones, S. W., Matthews, C. M., Wagg, B. T., Parker, P., & Ducharme, R. (2007). Slotted Liner Design for SAGD Wells. *World Oil*, 67–75.

Yamada, K., & Furui, K. (2018). Efficient Integration Method of Large-Scale Reservoir Compaction and Small-Scale Casing Stability Models for Oilfield Casing Failure Analysis. In *SPE Asia Pacific Oil and Gas Conference and Exhibition*. Society of Petroleum Engineers. https://doi.org/10.2118/192004-MS

Yassine, A., Joglekar, N., Braha, D., Eppinger, S., & Whitney, D. (2003). Information hiding in product development: the design churn effect, *14*(3), 145–161. https://doi.org/10.1007/s00163-003-0036-2

Yusuf, Y., Baldygin, A., Sabbagh, R., Leitch, M., Waghmare, P. R., & Nobes, D. S. (2017). EFFECT OF ASPECT RATIO ON PRESSURE LOSS AND CHARACTERISTICS OF LOW REYNOLDS NUMBER FLOW THROUGH NARROW SLOTS. In *ASTFE Second Thermal and Fluids Engineering Conference*. Las Vegas, NV.

Zappia, I., Parlanti, D., & Paganelli, F. (2011). {LiSEP}: A Lightweight and Extensible Tool for Complex Event Processing. In *2011 {IEEE} International Conference on Services Computing*. Institute of Electrical and Electronics Engineers ({IEEE}). https://doi.org/10.1109/scc.2011.63

Zeng, H., & Luo, J. (2015). *Award Details: Surface properties of slotted liners and associated interfacial interaction mechanisms in oil sands extraction process*.

Zhu, D., Bergerson, J. A., & Gates, I. D. (2016). On fingering of steam chambers in steam-assisted heavy oil recovery. *AIChE Journal*, *62*(4), 1364–1381. https://doi.org/10.1002/aic.15121

Zhu, D., Leitch, M., Wang, J., Shi, X., Gong, L., Aghaie, E., … ZengZh, H. (2016). Evaluation of an Advanced Metal Bonded Coating Technology for Improved SAGD Performance. In *SPE Latin America and Caribbean Heavy and Extra Heavy Oil Conference*.

Zhu, D., Wang, J., Su, Y., & Gates, I. D. (2016). Nonlinear Dynamical Instability Analysis of Steam-Assisted Gravity Drainage {SAGD} by Using Reservoir Simulation. In *{SPE} Canada Heavy Oil Technical Conference*. Society of Petroleum Engineers ({SPE}). https://doi.org/10.2118/180753-ms