AC 2012-4705: KNOWLEDGE-ENABLED ENGINEERING DESIGN: TOWARD AN INTEGRATED MODEL

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Information-Rich Engineering Design (I-RED)
Integrating Information Literacy with Design Activities

Abstract

Librarians and engineering faculty have long understood that design is one of the defining processes of the engineering profession. In an increasingly knowledge-driven society, students need to efficiently locate, assess and integrate relevant information into their design process so that they can develop innovation solutions to emerging complex, global grand challenges. Increasingly, engineering curricula are incorporating design as early as the first year, but a question remains as to how effectively information literacy is being integrated into these early experiences of design. For example, the *Engineering Change* study found there has been very little improvement to lifelong learning skills in engineering graduates over the last decade, and indeed lifelong learning, one indicator of information literacy skills, was the lowest rated of the ABET student learning outcomes. [1]

Both librarians and engineering educators have studied the use of information in an engineering context, but our knowledge of the possible synergies between information literacy and engineering design is limited. This paper presents an integrated model of Information-Rich Engineering Design (I-RED), providing a detailed articulation of the specific information needs at different stages of the design process. Derived from both literatures, this model attempts to bridge the language and conceptual divide between librarians and engineering educators, to facilitate deeper and more meaningful collaborations between the two groups

1. Introduction

Design, or more generally the conception and realization of new products, systems or processes, is a defining characteristic of engineering. This idea is captured in the quote attributed to Theodore von Kármán that: "Scientists study the world as it is; engineers create the world that never has been." Design is best used as a verb, the act of creating something, rather than as a noun, the documents or artifact that is the outcome of the process of design. While engineering educators often characterize engineers as "problem solvers," this definition has been challenged as design is much more socially engaged, exploratory and creative act than is captured in more analytical "problem solving," even where this is understood to include problem identification and formulation.[2] More recently the term "design thinking"[3] has caught hold as way to encapsulate the many cognitive and social dimensions of what is involved in the act of design in the context of new product development, with an emphasis on user-centered design.

In the educational process, design projects provide an opportunity to integrate and apply content knowledge, but perhaps more importantly, practice using the professional skills, often erroneously referred to as 'soft skills' that are key to success according to the *Engineer of 2020* report.[4] The role of information in design has been investigated by many groups over the past two decades. Mosberg et al[5] found professional engineers rated 'seeking information' as the fourth most important design activity out of a list of 23. Ennis and Gyeszly[6] also found information gathering integral to design for professional engineers.

Despite the perceived value of information gathering, Condoor et al[7] found students lock into a single solution and don't explore alternative design possibilities. While Atman et al[8] found seniors gathered more information than first-year students, the quality and process of information gathering continues to be a concern. Ekwaro-Osive et al[9] found .1% of student effort was spent doing 'library research,' and most of the information related activities carried out by the students studied involved 'planning to gather information.' Denick et al[10] found students relied too much on lower quality web sites rather than more appropriate formal publications like handbooks in their design reports. Wertz et al[11] found similar results, and further than students frequently mis-applied information they did gather. These results are in line with the results of Head and Eisenberg's[12] national survey of students, in which less than a third of respondents had a research strategy, and three-quarters had difficulty getting started on a project.

The authors contend that, in order to improve information gathering and application in design projects, a more integrated understanding of the role of information is required, so targeted instruction can be created and information gathering spread throughout the design process instead of being considered an add-on 'literature review' at the beginning or end of a project. However, in order to integrate the development of information literacy knowledge and skills into the learning of engineering design, first we need to have a working definition of both. This allows us to identify similarities and synergies that can be exploited so as to reinforce the interdependence between thinking as an engineering designer and leveraging of vital information of diverse types from many different sources as a value adding process, central to the creative process and hence innovation.

2 Model of Engineering Design Activity

Engineering design is a recursive process that results in artifacts – physical or virtual – which may be 'new-to-the-world' or simply variants on already existing things. Design involves both the use of existing information and knowledge and the generation of new information and knowledge. There is no universally agreed upon model of the engineering design process, in terms of various stages or tasks, inputs and outputs at each stage and the terminology used. Textbooks on engineering design typically include some form of model that sets out the process as a series of steps or stages with feedback loops and iteration.[13] Some of these models attempt to describe the various stages in a general sense while others are more prescriptive and give considerable detail about the various activities to be undertaken and in what order.[14] These models usually begin with a process of need finding and/or problem clarification and definition, moving to the generation of concepts and then the selection of a preferred concept, followed by the "fleshing out" or embodiment of the preferred concept into a preliminary solution which in term is developed into a detailed solution.

For the purposes of this paper, we use the following generic model (see Figure 1) of engineering design activities developed by one of the authors and used successfully for many years to introduce design to engineering students.[15] The five activities in the model are expressed as verbs. Some authors use the term 'design' as a noun, the outcome of the creative process, while others use it as a verb, the act of designing. Unfortunately, the word is often used interchangeably as a noun and as a verb, which can be confusing. This model uses design, and its activities, as verbs. Unlike other models of engineering design that focus almost exclusively on the stages or phases of the design process, this model includes explicitly the team doing the design work.

Activity	Relevant Issues Considered and Example Tools Used in this Activity
Organize *your team*	Code of Cooperation; active communication (LACE); team lifecycle; plan; Gantt charts; budget time; assign roles; track progress; maintain team; improve processes
Clarify *the task*	Analyze the brief; ask questions; estimate order of magnitude; risks & opportunities; scope work; context diagram; how-why diagram / objective tree
Synthesize *possible solutions*	Existing artifacts; prior art including literature, experts; nature; use metaphors; brainstorm; sketch ideas; morphological charts; prototype,.
Select & Refine *your preferred solution*	Visualize / model / simulate; estimate costs; manage risk & opportunity; controlled convergence; decision matrix; check your work.
Communicate *solution to persuade others*	Know audience; know your story; prepare thoroughly; use multiple media / pathways; improve report writing skills; extend presentation skills.

Figure 1: Generic Model of Engineering Design Activity

This model focuses on activities up to the point where the proposed solution is documented such that it can be made and implemented. Of course, the complete lifecycle of a new product, system or process includes the subsequent processes of manufacture, installation, commissioning, operation, maintenance, updating as technology changes, retirement from operation and re-use or recycling of the component elements.[16] The lifecycle also includes, for example, the training of users or operators or other service or support staff and provision of necessary support infrastructure and spare parts.

Decisions made in these early stages of the product realization process shape the subsequent or downstream life stages including such things as the whole of life cost of the product, system or process being designed and its overall sustainability.[17] Thus, the earlier relevant information is introduced the larger its impact on the entire product lifecycle, hence the critical importance of integrating information literacy (broadly defined) as early as possible into the design process and blending it into the education of engineering students as they learn to think as engineering designers.

3 Model of Information Literacy

The ACRL Information Literacy Competency Standards[18] provide a guide to student outcomes expected of information literate students. While providing a list of skills, however, the ACRL standards do not provide a roadmap of which skills are used when in a research (or design) process. The Information Search Process[19] does provide such a process model, and while grounded in traditional social sciences research (a 'term paper' approach), the stages of the process have been found to hold true in other disciplines as well.[20]

The Information Search Process (ISP) contains six stages: initiation, selection, exploration, formulation, collection, and presentation. Briefly, these stages are defined as follows:

- *Initiation*, when a person first becomes aware of a lack of knowledge or understanding and feelings of uncertainty and apprehension are common.
- *Selection*, when a general area, topic, or problem is identified and initial uncertainty often gives way to a brief sense of optimism and a readiness to begin the search.
- *Exploration*, when inconsistent, incompatible information is encountered and uncertainty, confusion, and doubt frequently increase and people find themselves "in the dip" of confidence.

- *Formulation*, when a focused perspective is formed and uncertainty diminishes as confidence begins to increase.
- *Collection*, when information pertinent to the focused perspective is gathered and uncertainty subsides as interest and involvement deepens.
- *Presentation*, when the search is completed with a new understanding enabling the person to explain his or her learning to others or in some way put the learning to use.[21]

These stages roughly define a research process that starts from problem definition and scoping to topic selection, thesis formation, documentation and, finally, communication. The first three stages are characterized by the search for 'relevant information,' while the last three stages are characterized by the search for 'pertinent information.' Fosmire[22] developed a map between ISP concepts and the engineering Informed Design Model (IDM) of Hacker and Burghardt.[23] While the IDM model only explicitly indicates one stage in which the designer 'researches and investigates' the problem, Fosmire found that, in fact, one can associate stages of the ISP with each stage of the Informed Design Model.[24]

4 Information-Rich Engineering Design (I-RED) Model

To more fully explore information use and creation associated with different activities in engineering design, we propose an Information-Rich Engineering Design (I-RED) model that integrates the generic design activity model (section 2) with the Information Literacy Model (section 3). It is comprised of six phases that correspond to the five design activities above, except with the 'select and refine your preferred solution' activity being split into two separate phases, as shown in Table 1.

Table 1: Information-Rich Engineering Design (I-RED) Focus Questions

Phase	Focus Question	Corresponding Design Activity
1	Who are the team?	*Organize* your team
2	What are we doing?	*Clarify* the task
3	What are our options?	*Synthesize* possible solutions
4	What will it be like?	*Select* your preferred solution
5	What are the specifics?	*Refine* your preferred solution
6	What do we tell others?	*Communicate* your solution to persuade others.

To reflect the idea that information is sought to enrich design, the six I-RED phases are expressed as a series of focus questions. This approach aligns with the notion of design as a question asking process.[25] Pilerot and Hiort af Ornas follow a similar approach in formulating guiding questions from not only a process but also a product oriented perspective.[26] For simplicity, I-RED approach concentrates on 'product-oriented' focus questions and treatment.

The I-RED model locates the six phases on an 'information space' with the orthogonal axes for the variety of knowledge domains and the level of specialization in a given domain as shown in Figure 2. The location of each phase indicates the relative 'breadth' and 'depth' of the types of information sought and/or generated in the corresponding design activity.

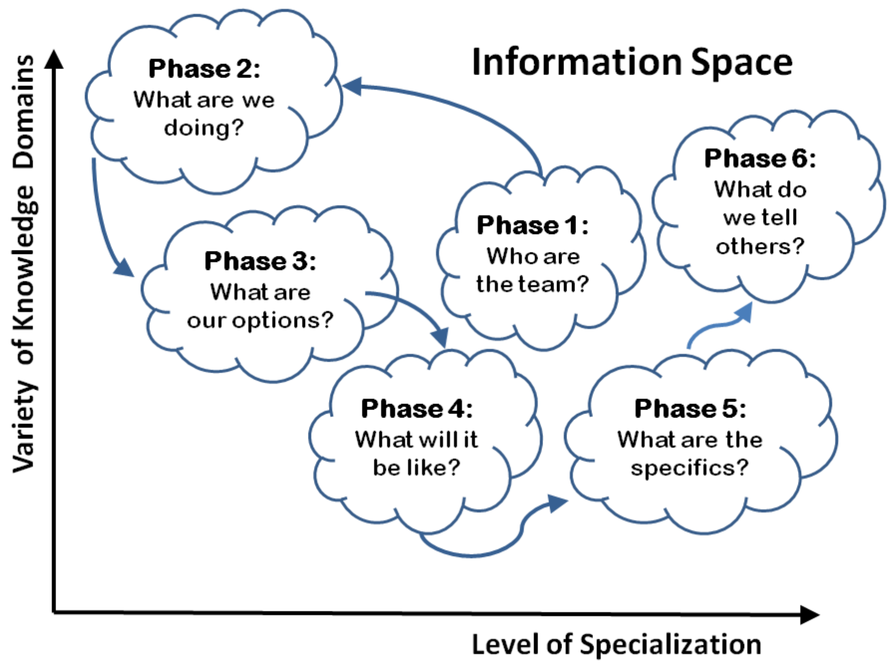

Figure 2: (I-RED) Information-Rich Engineering Design Model

These six phases are described briefly in terms of the particular types of design questions that lead to information seeking and/or information generation in each phase. Within each phase the Information Search Process (ISP) moves from exploration within uncertainty towards a focus on more pertinent information that define the later part the phase. At a more macro-level the overall trend in information seeking and generation across all six phases also follow the ISP stages. As a project proceeds, the feelings of the team members tend to follow those described by Kuhlthau, i.e., they go from uncertainty, to optimism, to confusion and doubt, which give way to greater clarity, and a sense of direction leading to hopefully satisfaction and accomplishment.[27]

4.1 Phase 1: Who are the team?

In forming a design team for a particular project, ideally we seek to gather a range of disciplinary backgrounds with sufficient levels of knowledge and experience and complementary personal attributes and professional skills. Factors that influence team performance include the range of technical knowledge and skills, temperaments and work styles (e.g., starters - finishers, big-picture people - detailers), organisational & leadership skills, and oral and written communication skills. In engineering design classes within a single disciplinary area the diversity of technical knowledge is limited.

One set of skills often overlooked when *organizing* a design team is the level of information literacy of the members. By including team formation as part of the I-RED model, attention is focused on the need to establish a core capability amongst the members to be able to identify, locate, gather, analyse, synthesize and share information within the team and with other stakeholders. The information literacy of the team sets a foundational baseline in terms of their ability to seek and share information effectively, which in turn is a key determinant of the overall effectiveness of the design work they undertake.

4.2 Phase 2: What are we doing?

In this phase the team attempts to *clarify* the true nature of the problem, need, or opportunity before them and to create an 'engineering problem statement.' The client might give a preliminary statement, like "I need a water purification system for a community of 2,000 people." From that initial statement, the team must determine what specific objectives the client may have, quantify and clarify the specific requirements, determine the constraints or opportunities, including the kind and amount of resources available for the solution. Much of this phase involves working with the client to better understand their own expectations. Sapp Nelson[28] found that the library science technique of reference interviewing can facilitate better elicitation of client requirements.

This phase also includes gathering preliminary information, e.g., the different types of purification systems, specific health risks of unclean water, and the local cultural/economic/political environment, in the case of the water purification example. Seeking out such information can help the team craft more pertinent questions for the client, helping them articulate constraints or objectives that they didn't know they needed. If there are regulations or other legal requirements, for example, clean water standards, then those are *de facto* constraints on any solution.

In general, the information requirements in this phase correspond mainly to gathering background information. General sources of information, such as encyclopedias, trade magazines, or handbooks, can give an overview of the major technologies being used to solve the problem. Codes and regulations will provide guidance on legal constraints. When teaching the informational component of this phase, focusing on the Initiation stage of the Information Search Process is the most important. This is the phase when the student will need to determine what information they know and what information they still need to find. Often with novices, 'they don't know what they don't know,' so they have difficulty articulating the need for information. Providing students with some structure for asking questions can facilitate them moving beyond an 'ignorance is bliss' phase and get them to engage with 'what they don't know.'

4.3 Phase 3: What are our options?

In this phase, the team consolidates and prioritizes a list of design requirements uncovered in the previous phase and explores potential design solutions that could meet those perceived needs and constraints. This is a very creative phase, involving brainstorming and other activities focused on idea generation and the *synthesis* of possible solutions. A valuable trigger for this is to explore the 'prior art,' solutions to similar problems that others have designed, and other technologies that might have novel applications to this problem. In order to enlarge the range of potential options to the fullest extent possible, an eclectic range of information types and sources need to be consulted. While the patent literature might be the most obvious source of information on specific technologies, at this phase of the process, where the emphasis is on developing a large number of possibilities, a more efficient way to investigate prior art might be to peruse the popular literature for reports of other solutions, including material provided by engineering firms, non-profits, or other organizations that have worked on similar problems.

As options are created and articulated, the team needs to determine not only how to build it, but also how it will be used after fabrication, how it will be maintained, and what will happen when it reaches the end of its life-cycle (recycling or re-use, for example).

4.4 Phase 4: What will it be like?

Initially in this phase, the conceptual designs are evaluated to determine which solution will finally be *selected* for implementation. This selection process requires the ideas generated previously be fleshed in the form of basic configurations that can be evaluated, for instance, as a computer model to determine whether these preliminary designs are feasible and practical. Often this is a hands-on phase of design, where the team makes simple or more sophisticated prototypes and conduct tests to see if they meet the design specifications. To facilitate testing of the ideas, an overall system might be decomposed into a series of sub-systems that can be evaluated. In that case, the inputs and outputs of each sub-system will have to be determined to ensure compatibility and interoperability.

For this phase, standard testing processes, laboratory and experimental procedures, and information about appropriate simulation/modeling software could all be needed. In addition, one needs to learn about and understand the underlying theories that go into the models. This enables the team to determine whether a particular model is appropriate for the use case of the design problem, and whether, for example, the results can be extrapolated from a model to the full scale. Additionally, the management of original data gathered during prototyping and testing needs to be carried out appropriately. As Carlson et al[29] note, data information literacy is a robust new area for librarians to apply (and teach) information management skills for the curation of data.

4.5 Phase 5: What are the specifics?

In this phase the focus turns to *refining* the solution by developing and documenting an increasingly detailed description of precisely what the product, system, or process will be like. This is an information intensive activity, as the selected preliminary design is turned into something that can actually be built. For example, one has to select the actual materials or products used in the design, determine whether those materials will meet any appropriate codes and regulations for performance, and make sure that the design will operate with any other artifacts that are required. Simple things like, will pieces fit together, can you service the component without taking apart the entire artifact, and can the output of one stage of the artifact be used as an input in the next stage are all important to resolve in this phase of design.

For this phase, handbooks, product catalogs, and component specifications are all important to make sure that the result is practical and achievable. Patents will shed light on the more cutting-edge technologies that could be licensed for use in the project.

It should be noted that, although these examples may look like manufacturing design, the concepts can be thought of more abstractly. For example, writing computer code for a software program involves the construction of modules and 'objects,' many of which may come from pre-existing standard libraries. As a result, it is very important that the output of an object is in a format and with appropriate units that can be used in a subsequent routine.

4.6 Phase 6: What do we tell others?

In industry, once the detailed design work is completed the description of the product, system or process needs to be communicated to those who will make it, install it, operate it, maintain it, update it, and even dismantle and recycle components of it. Additionally, the design organization will want to capture the information generated during the design process, including any computer models and modeling data, tests plans and data, mock-ups, functional prototypes and the like. It is especially important at this point that information is well-documented. Others will be using the information presented in this phase, so they need to know where that information exists. For example, how to find the safety codes for operation or the material composition of components for potential recycling. Correct and complete information about supplier information, codes met, availability of replacement parts or authorized maintenance all are important in the final documentation.

The technical and operational documentation for the new product, system or process also needs to be persuasive to convince the client that this is the best possible solution, as well as contain accurate information. Benchmarking data, recommendations from unbiased sources, and comparison charts against competing technologies all may be useful in this stage. Gathering of images, tables, or graphs, properly documented, can aid in communicating the primary message.

4.7 Examples of Information Seeking in each I-RED Phase

Table 2 provides a very short list of the sorts of questions that might trigger information seeking in each phase of the I-RED model. These questions can provide the focus for in-class activities, components of documentation during each stage of the design process, and generally, as talking points to begin conversations between librarians and engineering faculty trying to understand how to improve the information content of student projects.

Table 2: Focusing Questions for Information-Rich Engineering Design (I-RED) Phases

I-RED Phase	Examples of Questions that Prompt Information Seeking / Creation
Who are the team?	• What is the level of specialization and variety of technical and other knowledge across the team members? • What is their level of proficiency in information seeking and critical evaluation? • What additional information seeking skills are required? • How might additional information skills be best developed?
What are we doing?	• What are the historical, social, cultural, political, geographical, and economic contexts of the problem? • Who are the stakeholders? Who will “use” this product, system or process throughout its lifecycle – from the cradle to the grave? • What are the most important requirements or functions to the various stakeholders? Which are absolutely necessary (needs), and which are discretionary (wants)? • What are the measures of success for all stakeholder groups? • What codes or regulations do the project and the end product have to comply with?
What are our options?	• What are some examples of solutions for this kind of problem? • What products, systems or processes exist to tackle this or similar needs or opportunities? • What technologies might be used to tackle this need or opportunity? • What is required to create, operate, and maintain this technology? • Does relevant benchmarking data exist for competitor products?

I-RED Phase	Examples of Questions that Prompt Information Seeking / Creation
What is it like?	• How do the technologies scale with size, speed, etc., from a prototype to full-scale implementation? • How would you test for different specifications of performance? • Are there formalized standards for conducting these tests, to enable comparison among products? • What tools would help in designing a full-scale model? What modeling or design software do professionals use in this field? • How do proposed new solutions compare to existing ones in terms of performance, user desirability, financial viability, or other indicators of success?
What are the specifics?	• What properties does a component have and what does it need to have to work properly within the system? • What components need to be fabricated, and what properties do they need to have to work with the rest of the system? • What components already exist that can used as part of the solution? • What are the standard inputs/outputs for your systems or sub-systems (for example, appropriate networking interfaces, size of conduits for moving materials)?
What do we tell others?	• What new information has been generated during the design process and how important/valuable is it? • Is all the pertinent information gathered /created and used in the design process been fully documented and catalogued including calculations, models, graphic images, tables, and other non-textual information? • Does the documentation contain information about all phases of the life-cycle of the project? • Is the documentation prepared and presented in a form and style most appropriate to the future user of that information?

5 Discussion

This model provides a descriptive rather than prescriptive approach to identifying the informational opportunities for integration into the design process. Attempts were made to keep both the informational and engineering design components as general and generic as possible so that the model can be applied to a wide range of engineering disciplines. The authors also attempt to step outside of the jargon of both library science and engineering design to enable practitioners of both sides to talk directly and productively about student and project needs. The motivating factor of the model is to determine at each stage 'what information do I need now to move the project forward, and how I can acquire and use that information.' Instead of requiring students to do a 'literature review' at the beginning or end of a design project, this model provides guidance for information gathering activities that can continue throughout the life of project, and not as a stand-alone product. This should provide an integrated approach that will enhance the richness of the design of the final artifact.

It should be emphasized that design as a learning process creates knowledge as well as consuming it. It provides opportunities for students to contribute to a larger knowledgebase. In the real world this would likely appear in a corporate intranet or knowledge management system, but in the academic world this also increasingly occurs with the advent of large-scale projects wherein students may work on a multi-year project for a semester or two, but then may graduate or move on to another project. They have moved the project forward but need to hand it off to downstream teams without a loss of knowledge that needs to be re-created by the new team.

The type and scope of information sought (and generated) in engineering design activities is very broad. Design information is not limited to documents like handbooks books and catalogues, whether in physical or electronic form, but includes still and moving images, multidimensional data sets including product and geographical information, the spoken word as well as physical and virtual artifacts. The sources for and modes of gathering, capturing, analyzing/interpreting, storing and sharing this eclectic range of information is enormous and ever-changing. This has critical implications for both the development of information literacy skills in students and the work of university librarians who support design projects in engineering schools.

The proposed Information-Rich Engineering Design (I-RED) model combines conceptions of the design process and information literacy to create a logical framework for integrating the development and use of information skills into engineering design classes. This model also draws on the experience teaching of engineering design over many years in both the USA and Australia including numerous collaborations with librarians to embed instruction on information literacy, as it relates to design projects, within the classes.

The next stage of this work will be to test and refine the model by creating a series of classroom interventions for supporting information seeking and documentation, observing the outcomes and then refining the intervention. This iterative, inductive approach is adapted from design thinking; i.e., prototyping your ideas in order to develop a deeper understanding of the problem while simultaneously developing the solution. This exploration will be done in a multidisciplinary engineering design class, which has the advantage that the model of design can remain relatively generic. Subsequently we will test the model in specific engineering disciplines (e.g., mechanical, civil, electrical, bio-medical, computer).

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