Engineering Environments in the Information Age: Research Challenges and Opportunities

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Abstract: This paper examines changes to the contemporary product engineering cycle resulting from the Information Age and identifies information-related obstacles that correspond to the human dimension of information overload in engineering. These obstacles may explain why increases in productivity have been disappointing and why information technology has not been able to satisfy the increasing demands placed on contemporary engineers. Three productivity impeding categories are discussed: (a) detail overload, (b) constraint overload, and (c) versatility overload. The authors suggest how new emerging paradigms and technologies can be harnessed to alleviate the identified difficulties. Three directions for improvement are discussed: (a) bringing computer tools into the engineering process earlier, permitting more extensive exploration and informed selection of alternatives, (b) improving human-computer interfaces towards in-context natural interaction, making information exchange more fluent and fast, and (c) transforming computers from passive to active self-initiated engineering aids that can suggest alternatives and convey relevant information. The paper discusses applications to areas such as design, manufacturing, simulation, quality assurance, and maintenance.

Keywords: Engineering environments, Information technology, Life cycle engineering

1. Introduction

Over the past decade, changes in product development processes and increased consumer demands have dramatically influenced engineering working practices and targets [1,2,4,12]. Development cycles for products have been reduced from several years to several months. Marketing deadlines have become crucial, as most profits are earned within a short period after product release. Extensive competition has shifted the focus to product quality, reliability and service. Niche markets and custom design for small quantities have become standard practices, and new issues such as safety awareness and environmental considerations [1] are placing increasingly complex constraints on design.

The information technology (IT) revolution has made its appearance concurrent to this relentless escalation in product engineering requirements. IT has offered hopes for improved productivity despite these increasing demands. The wide availability of personal computing power, virtually inexhaustible sources of information and an abundance of computerized engineering tools have created great expectations. Nevertheless, the introduction of new information technology tools alone has not brought the anticipated rise in productivity; in fact, a disappointing slowdown is now observable. For example, U.S. companies spend nearly 43% of their capital budget on IT hardware alone, more than on any other durable equipment. Still, over the past 30 years productivity growth in the world's seven richest nations has dropped from 4.5% down to 1.5% in recent years, and even this minor growth can be explained by factors other than IT [3].

While the debate over the productivity puzzle continues [3], it is evident that the technological revolution of the past decade has created a paradoxical situation whereby engineers are both the beneficiaries and the victims of their own success. Users have difficulty making effective and efficient use of the extensive technological possibilities and information available to them. This overload is particularly evident in the field of engineering, where the growing demands placed on engineers by their dependency on information flow, along with increasingly excessive amounts of available *details* and constraints, can be overwhelming. This surplus, if not wisely used, may result in higher operating costs, longer time factors, more mistakes, and generally inadequate exploitation of existing information and tools. Furthermore, endless sources of information and high rates of job change may make valuable information still harder to extract and good knowledge difficult to accumulate. Over-sophistication of computerized tools and availability of infinite options may sometimes do more harm than good.

Clearly, the above mentioned trends and others as well have brought about new difficulties as well as new opportunities. This paper explores these new problems and attempts to identify where and how new technologies can be harnessed to create a more productive future engineering environment. We specifically address the human dimension of information overload [7], which we believe to be one of the crucial parameters and bottlenecks of contemporary engineering in the Information Age.

2. Problem Statement

In response to the dramatic reduction in the product development time cycle, engineers are encouraged to use available technology rather than engaging in new research and development, since using existing and tested components is safer and usually more successful. This trend toward *design on demand* [2] asserts that a modern design process primarily involves modifying existing designs, merging outside resources and components, and extensive browsing through sources of information such as catalogues and the Internet. The demand for shortened cycles has also narrowed the scope allowed for exploration, as engineers need to converge earlier to a particular design concept, while market studies require exactly the opposite. Shared databases that can be accessed and modified concurrently by all members of a development team contribute to the overall increase in information handling

needs. Another human dimension affecting product development is that a typical engineering career is built by a number of short employment periods, precluding the reliance on a specific individual as a long-term information source.

As the role of information in the modern engineering life cycle becomes more dominant, related technology develops accordingly. Tools and sources of information are expanding and diversifying all the time. At the same time, however, the human capacity for absorbing information does not increase at a corresponding rate. We term this incompatibility as the *information overload* problem.

Three categories of the impact of overload on users can be identified in the engineering process:

1. ***Detail Overload:*** too many details and too much excess information to handle.
2. ***Constraint Overload:*** too many demands and considerations to satisfy.
3. ***Versatility Overload:*** too many options or possibilities to consider.

The most common type of *detail overload* results from direct use of unfiltered data from an expanding source. This source may be varied, ranging from an Internet search or a CAD/CAM model being interrogated or manipulated to a project database or analysis results. Detail overloads can arise from complicated maintenance and operating instructions, complex manufacturing conditions or incoherent organization of documentation.

In contrast, *constraint overload* occurs when the demanding circumstances place too many constraints on the designer without assigning any particular priorities. Reasoning under constraints has been the subject of intensive research, mainly for treating well defined sets of a single type of constraints. Constraint overload, however, occurs when considerations from all aspects of the process mount up, making it necessary to bridge constraints from different domains, such as functional constraints, marketing constraints, geometrical constraints, and financial constraints.

Even in the field of concurrent engineering, development options are numerous, and issues are often too broadly defined. This problem suggests the third type of overload, namely, *versatility overload.* The scope and breadth of definitions, virtually infinite sources and multiple targets together create a large search domain which is sometimes too vast to cope with. Similarly, engineering tools provide more and more options and sophistication. Custom niche designs and rapid development cycles have created a situation in which every product has several model versions, each with several variants. This often poses a problem both to the manufacturer and the consumer.

Several examples follow:

Computer Aided Design. As technology advances, products are modeled with an increasing amount of detail. Software itself is becoming more and more sophisticated and option-intensive. Modeling a product requires extensive experience and training, as does executing an analysis and interpreting its results. Users typically spend a considerable amount of their working time manipulating the model by zooming, panning, reorienting, filtering and redisplaying in order to see and access relevant information. The search for alternatives is becoming difficult due to increasingly complex and mounting constraints and the rapidly changing market. The search for components is becoming inefficient due to the inexhaustible supply of potential sources.

Manufacturing. The manufacturing stage is affected by information overload mainly at points when manual intervention is required such as machine setup, manual machining, assembly tasks and quality assurance. During these stages, the worker must perform various tasks rapidly and accurately. As manufacturing equipment and manufactured products become more sophisticated and as manufactured batches become smaller and more varied, the time, cost and potential for error in these operations increase.

Maintenance. Due to the numerous manufacturers, models and variants of increasingly sophisticated machines, it is more and more difficult to keep up with maintenance and servicing procedures. The physical maintenance operations themselves are not necessarily more difficult; the bottleneck is in knowing which one to perform for any given problem.

3. General Solution Strategies

The problem of information overload can be reduced by changing some of the key features of computer assisted engineering practices. We do not aim to suggest how existing tools should be improved or how manual operations should be automated. Rather, we have identified three general directions of improvement:

1. Bringing computer tools into the engineering process **earlier**, thereby permitting more extensive exploration, earlier detection of problems, and better informed selection of alternatives.
2. Improving human-computer interfaces towards ***in-context*** natural interaction, where information is presented with natural cues in its final context, thereby making information exchange more fluent and fast.
3. Transforming computers from passive tools to active ***self-initiated*** engineering aids that are capable of *suggesting* alternatives and conveying relevant information automatically when and where it is needed, based on the demands of circumstances rather than upon an explicit user request.

3.1 Earlier Involvement

One of the key factors in the engineering process is the *expert* [2]. Experts are crucial to the development process because they can predict many aspects (and problems) of a design at an early stage. Because demands are becoming more restricted and in-house experts are a rare commodity, computerized engineering tools must be incorporated earlier into preliminary design. Earlier incorporation of computerized engineering aids, however, is not a simple matter. During the preliminary stages, concepts are vague and details are defined only roughly; in contrast, most expert software requires accurate and well defined models along with the expertise for interpreting the results. The following capacities are therefore required:

1. Fast definition of **conceptual models** to convey key aspects of a design.
2. **Conceptual analysis** of rough models to reveal key qualities of a design.

Traditional CAD requires accurate data and dimensions right from the start, even if these can be subject to changes later on. The need to handle rough models means that the traditional CAD methodology of *"model and analyze"* is reversed. First, a rough concept is defined without dimensions or accurate information.

Next, a rough analysis is performed to get an idea of the implications of that concept. Only then, after further exploration, the specific rough concept is transformed to an accurate model. Thus, a product model is constructed only *after* analysis. However, a surprising amount of information can be predicted by analyzing a rough model at a preliminary stage. For example, Figure 1 shows how a rough conceptual design sketch of a sheet metal product has been interpreted [5] and analyzed [9] to convey approximate information about the number of required components, the optimal flat pattern, and aspects of the product's production cost.

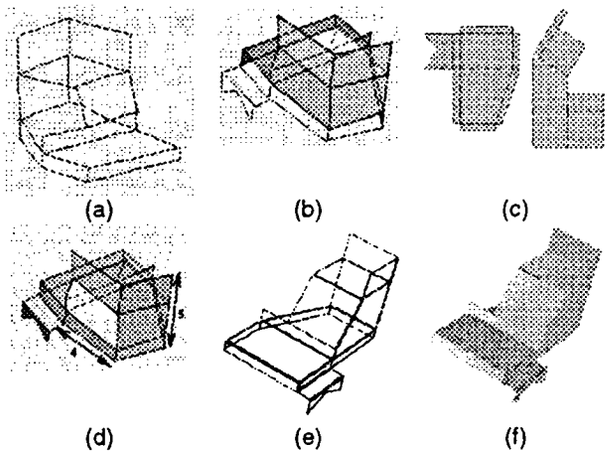


Fig 1. A rough modeling and analysis sequence of a sheet metal product, (a) rough sketch, (b) 3D reconstruction, (c) flat pattern analysis, (d) refinement by variational geometry, (e) accurate model, (f) simulation of final product.

Enabling definition of conceptual models is a difficult challenge. Rough concepts are conveyed among designers through intensive use of sketches [11], diagrams, verbal descriptions and crude prototypes. Based on this kind of input, the computer must construct a model sufficiently rigorous to perform a rough analysis. Analysis of rough models raises another challenge. Fuzzy mathematical approaches are needed; in the above example, the inaccurate geometry required soft rather than hard collision checks when seeking the flat pattern, as well as fuzzy versions of the AI search algorithm. Rough analysis must also conform to fundamental robustness principles. It must be invariant to small changes in the rough model, and must be able to extract and identify key analysis characteristics, so that it can provide a reliable figure of merit for a particular concept at the preliminary exploration stage.

3.2 Natural Interaction

User interfaces and man-machine interaction have a substantial influence on the efficiency of the design and production process. When using computer-oriented tools, such as menus, commands or keyboards, the user is forced to convey intentions, describe ideas and obtain information through terms and means supported by computer software and hardware. This requirement calls for a cognitive conversion process whereby abstract information is translated into an accurate descriptive language and operations. This additional load is detrimental to communication efficiency and effectiveness and may impede creative flow and impair the cognitive problem-solving process taking place at that instant.

Similarly, information communicated from the computer to the user is typically detailed and elaborate rather than concise. Natural interaction can play a significant role in alleviating this communication bottleneck. Natural interaction involves allowing humans to communicate with the computer using the same means they use to communicate among themselves. Natural interaction, therefore, must address two main issues:

1. The need to convey information using **fast and loose** descriptive language rather than accurate and elaborate specifications, and
2. The need to use means which are natural and **effortless** for humans, rather than those oriented at computers.

For example, Figure 2 shows a virtual drawing table (developed at the Technion) that supports natural pen-and-paper-like interactive sketching. Similarly, 3D geometry is better achieved via three-dimensional locating hardware and stereoscopic visualization techniques rather than letting the user use a preponderance of 2D techniques. Commands to the system are more naturally entered by voice activation and natural language processing. Application-specific metaphors can be used. The importance of natural interaction is even more apparent in out-of-office engineering activities, such as data collection, manufacturing and quality assurance.

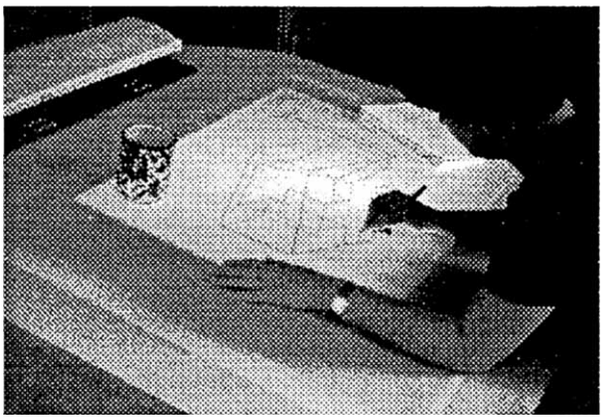


Fig 2. Virtual pen-and-paper-like sketching environment.

3.3 In-Context Interaction

A significant amount of overload is caused by the need either to embed or to extract information from its context. Using new technology, it is possible to employ direct embedding to eliminate the extraction phase. For example, a technical engineering drawing for quality assurance provides critical dimensions placed in the context of a geometrical shape. If the dimensions were shown directly on the product (using, for example, augmented reality), that part of the information would be redundant. Presenting information in context can thus drastically reduce information overload. Other examples of in-context information include presenting animated maintenance (Fig. 3) or manufacturing instructions on machine parts themselves using augmented reality, and displaying analysis results overlaid on a product model. Using augmented reality, a designer can design and test a part in the context of its final assembly or use the entire office as workspace for CAD. Conversely, in quality assurance, measurements are recorded directly from the model using a spatial locator. The computer can then know not only the value of the measurement but also which dimension is being measured, whether that measurement is critical, and whether the measured part complies with it.



Fig 3. Synthetic image of an augmented reality environment for guided maintenance.

3.4 Self-Initiative

Computers are usually conceived of as passive tools, yielding information upon request. This passiveness constitutes a major drawback, because it depletes one of our most limited resources: *attention*. According to [2], two of the most crucial entities in product development are the 'Generalist' and the 'Gatekeeper'. The Generalist is the one who challenges the current concept and says "Hey, why don't we do it differently...", while the Gatekeeper, seeing a team trying to solve a problem, proposes a solution: "Hey, I know where we can get this number...". Both these functions require *self initiative*. Traditional direct-manipulation CAD interfaces alone are not sufficient. Future engineering software will not merely respond to user requests but, based on previous activities and built-in knowledge, will anticipate user needs and actively seek ways to support the user, exhibiting *autonomy* and intelligence [13]. Software tools exhibiting these qualities are often termed 'agents'. Several examples follow:

1. **Automated alternative seeking.** Given a particular engineering solution the computer may search 'in the background' for alternative solutions that can provide the same functionality under the same constraints; once these alternatives are found, they are presented to the user. Even if the alternative is not satisfactory, it may stimulate the user to think in new directions. This capability requires automatic derivation of functionality and constraints, as well as automatic solution. The need to seek a variation on an existing solution rather than a completely new solution makes this capability feasible. Some examples include: replacing a part in a solid assembly with a lighter component that has the same function; identifying a new relevant component via the Internet; or verifying the correctness of analysis results and suggesting improvements. These goals require rigorous systematization of design knowledge and methodologies [10,13].
2. **Automated presentation of relevant information.** Instead of presenting the user with all available information, the system should be selective and self-initiate the presentation of relevant information that is appropriate at that instance. Examples include automatically selecting the best orientation of a CAD model for working on a particular area of the model (see [8] for similar application); automatically displaying the dimensions appropriate for a particular machining task; or automatic online guided maintenance (OGM) [6].

4. Conclusions

The Information Age, with its benefits and its overloads, is here to stay. Only by making inherent changes in the future engineering environment and in our perception of the role of computers as engineering aids can we make good use of its potential. In this paper, we have briefly discussed what seems to us to be the most crucial productivity-enabling factor: human information overload. We have reviewed some possible directions for improvement, namely, using computers early in the design process, employing more fluent and natural user interfaces, and transforming the computer from a passive to an active, self-initiating tool.

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