Title:
**50 Years after "Sketchpad": Has CAD Research Reached a Golden Age?**

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Introduction:
The Massachusetts Institute of Technology, MIT, project [2, 10] which resulted in the first interactive Computer Aided Design system "sketchpad" is usually associated with the beginning of the field of Computer Aided Design. 50 years after the beginning of this field, it is good to look back on the achievements to establish if CAD can now be referred to as a matured field of research. While Design research generally has had several attempts to investigate the nature of the field and the degree of maturity [ ], there are fewer contributions to do the same for CAD research, which can be considered a sub-domain of Design research. The few contributions consist of majority of views which think the field in not yet a matured field using terms such as the fact that field can be said to be "atheoretic" or pre-paradigmatic [3]. On the other hand, other researchers [5] think the field or aspects of it, such as solid modelling, can now be considered a matured field. There is, perhaps, some evidence on both sides. To clarify the debate, it would be useful if criteria employed for characterising whether a field of research is matured are employed to investigate the nature of CAD research. These criteria often point to contributions such that in Thomas Kuhn's book titled "The structure of scientific revolution" [6] where the term paradigm was introduced to define the state of a field that has achieved some level of maturity. These maturity criteria include whether there are consensus or clearly identified schools of thought on various aspects of the field such as: (1) The type of research questions and grand challenge the field is addressing; (2) Bodies of knowledge the field is based on and contributing to; (3) The type of research outcomes; (4) Methods of conducting research in the field; (5) Validity criteria for research outcome; (6) Cohesiveness and directed growth of knowledge contribution in the field.

Several research frameworks have been developed and address the maturity issues listed above, one of which is Blessing and Chakrabarti's Design Research Methodology (DRM) [1]. Other research frameworks have been developed in adjoining fields such as Information Systems. What, however, has been pointed out is that even when research frameworks are highly cited and researchers claim they use them, there is lack of consensus on what the contents of the frameworks are and how to apply them. This paper is therefore an attempt to explore how consensus in a research field such as CAD can be achieved, thus, hopefully, laying a foundation for the maturity of the field or for inherent maturity to be more visible. The paper is the author's personal enquiry and self-critique and it is hoped that it would generate useful response and debate from more experienced members of the CAD/CAM research community. Section 2 of this paper addresses how CAD research measures using the maturity criteria listed above. In section 3, we propose a framework to engender discussion by the research community illustrating its application with a re-interpretation of the author's works in CAD/CAM research.

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Application of maturity criteria to CAD research:
In this section the criteria listed in section 1 are applied to discuss the issues of maturity of CAD research.

*Research questions/Grand challenge in CAD research*
With the exception of papers such as that by Piegl [8], the author is not aware of many CAD papers that explicitly address fundamental research questions for the field. While the seminal work of "Sketchpad" [2] state very challenging vision of CAD, which is still relevant even 50 years after, the fundamental research questions behind this vision is not explicitly addressed and need to be further clarified, at least for less-experienced researchers such as the author of this paper. Without explicit grand research vision, the nature of the problem the field is trying to address is not clear. For example, in the seminal work of "Sketchpad" there were questions whether CAD should be Automated Design or Computer Aid of Design. 50 years after, has this type of fundamental question of the nature of CAD really been resolved by the research community? (Q1). The research community needs to come to a consensus on what it means (in a historically-grounded and philosophically grounded way) to aid or automate design (Q1.1).

*Body/bodies of knowledge addressed in CAD research*
One of the issues in CAD research is whether there is a consensus on the body of knowledge CAD is based on or contributing to (Q2.1). Contributions such as that of Hoffmann and Jaroslaw [5] and Shapiro [9] mention current bodies of knowledge that aspects of CAD such as Solid modelling draws on, pointing out that we can even go further "to the earlier methods of synthetic geometry employed by Greeks and Egyptians more than two thousand years ago"[9]. Representation of design objects (as in solid modelling) is one of the areas where some measure of consensus of the body of knowledge has been achieved. Other areas of similar success includes some measure of convergence of stages in the design process or stages in other CAD/CAM-related areas such as process planning. Are there reasons why consensus has been achieved in these cases? Can the success be replicated in other areas of CAD, and how? (Q2.2) While some of the contributions have made good attempts to build on these identified "kernel theories", it is necessary to ask the question: How has CAD contributed to these reference body of knowledge or become a reference field to other research areas (Q2.3); and do other CAD research output make any conscious efforts, as a research community, to identify the set of kernel theories being built on? (Q2.4).

Related to the explicit identification of the body of knowledge addressed is the cohesiveness of knowledge contribution in CAD research. The fragmentary nature of the outputs of the field has been mentioned by researchers. The outputs which mostly appear as "Yet another new algorithm/computer system" are usually not related to previous related work. Some researchers have identified the reason for this being due to the "Not invented here" syndrome, while others have mentioned that the fragmented nature of the field is due to different implicit philosophical assumptions underlying the approaches/methodologies/tools employed by researchers. How can researchers be enabled to uncover these assumptions or avoid them biasing their results (Q2.5). As part of an expression of the cohesion of knowledge contribution, can there be clarification of the relatedness of the various journals and conferences with a focus on CAD research? (Q2.6).

*Types of outcomes in CAD research, Research questions, Research method and the success/validity criteria*
This issue addresses the question of whether there is consensus on what constitutes valid outcome of CAD research (Q3.1). Similar questions are still being raised in Design research in general and adjoining research areas such as Information Systems (IS) where computers are applied. Research frameworks such as DRM [1] developed for engineering design and similar frameworks in the adjoining areas such as IS have characterised outputs from design research into: descriptive-I (including conceptual, descriptive, explanatory, predictive, normative studies), prescriptive and descriptive-II studies. Is there agreement in the CAD research community that this characterises the types of research outcomes we are trying to generate? (Q3.2). Among those who, to some degree agree, to these characterisation, there is the question of where the focus should be, i.e. descriptive vs prescriptive?

(Q3.3). For CAD, this addresses whether artifacts (usually algorithms and computerised design support tools), which are the majority of outputs reported in CAD research, on their own constitute knowledge contribution and in what ways.

There are issues for each of the possible types of outcomes relating to validity/evaluation/relevance of these outcomes. For example, is a prescriptive-focused solution without explicit descriptive-1 solution valid? (Q3.4); How can a prescriptive-focused solution be validated, especially since if it is focused on solving industry problem, it would require industry adoption of the solution and a long time of industry testing? (Q3.5); Is a descriptive-I focused research relevant enough to practice (sometimes what is referred in other fields as the rigour vs relevance dichotomy)? (Q3.6). Even for Industry-based prescriptive outputs, researchers have questioned whether they have enough relevance on practice such as commercial CAD development (Q3.7). As part of this relevance question, there is the need to ask if the support tool/artifact developed is evaluated with respect to how it improves design practice and not just as a computerised tool (Q3.8).

In addition to identifying outcomes, it would be useful for the research community to discuss and reach some consensus on types of research questions related to the research outcomes, with examples of good practice showing how shallow research questions/hypothesis can be avoided (Q3.9). Can we have some measures of consensus on grand research questions that needs to be addressed as is exemplified in matured fields like science in addressing ventures such as the Human Genome Project or Higgs-Boson particle project? (Q3.10). This needs to be followed by accepted research methods for answering the different types of research questions, with possible protocols and standard for replication and corroboration as in more matured fields like science and medicine, especially when addressing grand challenges as mentioned above (Q3.11).

Towards a matured research field:

In this section some of the questions raised in section 2 are addressed. A framework for discussing the questions is proposed so that other researchers can contribute to it. One way of doing this is to make the discussion process transparent as in the visual form of a concept graph (shown in figure 1). Using the framework, researchers can examine facts that can be employed to answer each question, making efforts to uncover and clarifying assumptions underpinning those facts. As part of ensuring transparency of the process, when facts are combined together to draw a conclusion, the concept used to arrive at the conclusion is noted. The framework is applied in the following section to answer some of the questions raised in section 2.

*Clarifying the problem of vision and grand challenge of CAD research*

While the author does not agree with blanket automation of design on grounds such as inviolability of human ultimate responsibility for consequences of the results of design, his unfounded assumptions relating to this view needs to be uncovered and corrected. With these assumptions clarified, the author was able to accommodate the vision of automated design as an experiment to determine which design tasks can be automated without violating human responsibility and as a means of better understanding what design tasks are and how better to develop tools to support them. This unified for the author the two hitherto seemingly conflicting perspectives of Computer Aid of Design and Automated design. This experimental approach was found to be useful in the author's previous research [7].

*Clarifying the problem of outcome, research questions, research methods and validity/success criteria*

To reach a consensus on acceptable research outcomes for CAD research, the issues such as Q3.4 has to be addressed, with an acknowledgement of the author's starting bias being in the end of the spectrum that sees descriptive-I-focused research as the better option. The author has to uncover and confront unfounded presuppositions on why a prescriptive-focused research is not a good option, such as: (1) only codified and scripted knowledge is acceptable knowledge contribution; (2) It is not possible to conclusively test artifacts in realistic practice; (3) wanting to achieve a positive effect in practice will bias research. Confronting these pre-suppositions and correcting them, the author was able to reach the following understanding: (1) It can be assumed that the principle on which a prescriptive-focused solution has been shown (either by literature or some previous independent research) to work to some extent, (2) The prescriptive-focused solution is developed and possibly lab-tested first and then introduced and tested in practice to identify the degree of success it could have (for example in comparison to lab-tested results) and the factors influencing this success. (3) The prescriptive solution can also be part of a repository thus making it publically available as shared understanding, hence a contribution to knowledge (e.g. like the open source projects project like Linux operating system). With this understanding, one could then integrate one's preferred approach of "descriptive-I focused Knowledge contribution" with a "Prescriptive-focused knowledge contribution perspective, achieving consensus.

*Building cohesive body of knowledge-the example of feature taxonomy*

The example here is a self-critique of how not to build a cohesive body of knowledge from our attempt to extend the taxonomy of basic prismatic subtractive features by Gindy [4] to include rotational depression features and then protrusion features of the prismatic and rotational types [7]. A point we did not mention is how our work has contributed in making the research community see the taxonomy of Gindy in a better light. It is not the spirit of building a body of knowledge to indicate that our taxonomy is more general than Gindy's. Our taxonomy was general in an abstract sense as it does not address a specific manufacturing application, but shape features in general. When it is applied to a specific manufacturing operation it becomes like the taxonomy of Gindy which is more practically applicable. This interpretation would have been a better way to achieve a more cohesive body of knowledge.

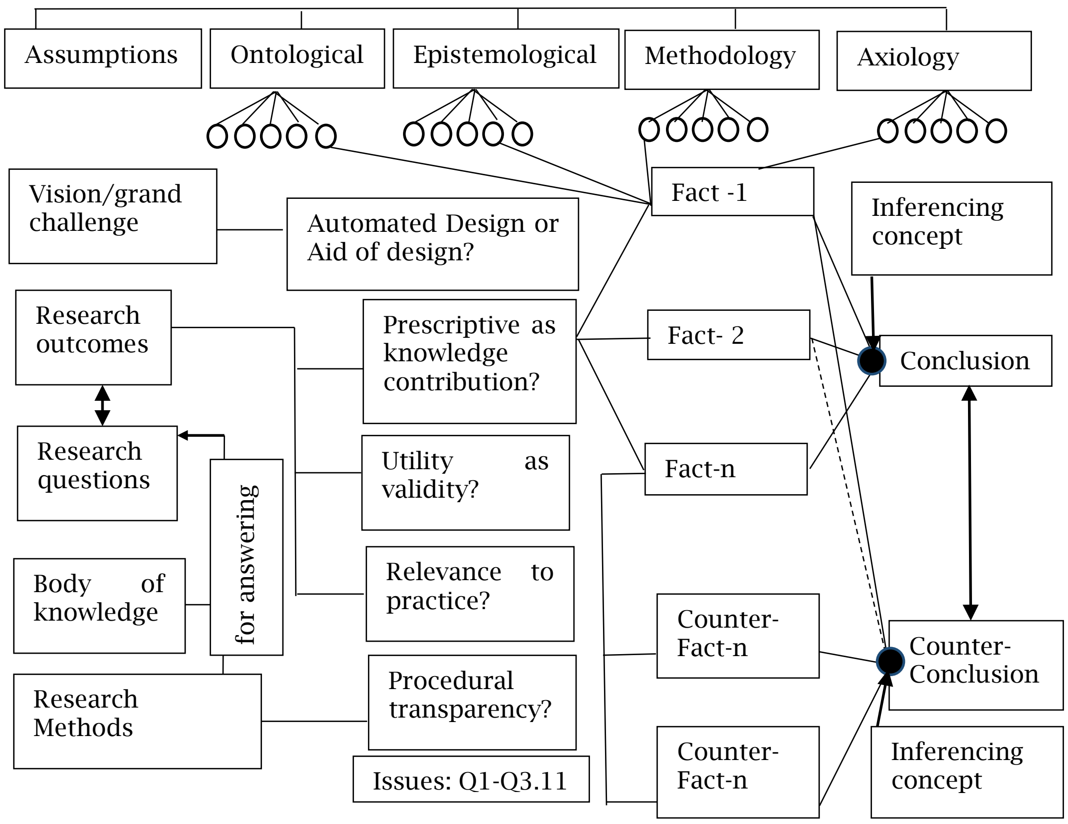


Fig. 1: Concept map for making research consensus process transparent.

Conclusions:

In this paper, criteria for characterising the maturity of a research field was applied to CAD research, resulting in about 20 questions to be addressed by the research community in order to reach some measure of consensus. A framework for addressing these questions was proposed and applied to some of the questions using the author's research as an example, leading to some of the following findings:

- When unclear terminologies and unfounded presuppositions are uncovered and clarified, the various seemingly conflicting views on research vision, types of research outcomes/validity, and research methods arrive at a consensus.
- With this approach, the potential for consensus and hence maturity in CAD research can be made more visible.

In future the following steps are suggested to take the research forward:

- Need for more empirical basis for the discourse presented in this work;
- Implementation of the suggested consensus framework in an electronic online forum, with facility for visual display of the progress of the discussions and testing;
- Currently, most questions are from the author's perspective. There is need for questions from the perspective of other members of the CAD/CAM community, especially researchers more experienced than the author.

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